Proposal to Test Improved Radiation Tolerant Silicon Photomultipliers

F. Barbosa, J. McKisson, J. McKisson, Y. Qiang, E. Smith, D. Weisenberger, C. Zorn

Abstract

Jefferson Laboratory is in the process of testing a 1st article test sample (quantity = 80) of silicon photomultiplier (SiPM) arrays in the expectation of purchasing a full 4,000 of the arrays for use as the photodetector in the barrel calorimeter of the GlueX detector. Radiation tolerance to high energy neutrons was the only characteristic that raised any doubt concerning the use of the solid state detector in this application. Tests of SiPM samples with neutrons from beamline backgrounds and an Am-Be source combined with simulations of expected neutron backgrounds in the 10 year lifetime of the GlueX experiment indicated that the devices could survive, but only by reducing their operating temperature to 5°C during beam operation to reduce their dark noise. The SiPM vendor – Hamamatsu Corporation – has expressed interest in improving the radiation hardness of future versions of SiPMs to improve their general use in nuclear and particle physics experiments. They have identified some possible means to achieve this. The main point of this proposal is to (1) request $35K to aid with the cost of producing these new SiPM samples, and (2) request another $5K (for a total request of $40K) for modifying or improving the present experimental setups.

Contact person: Carl Zorn, Jefferson Lab, carl.zorn@jlab.org, 757.269.7449

Background

Silicon Photomultipliers (SiPM) have developed rapidly during the last decade or so. Also known technically as limited geiger-mode avalanche photodiodes, they have already garnered a large interest in nuclear and particle physics as well as in medical imaging. A detailed review of their operation, history and applications can be found in reference [1].

In basic form, they consist of an array of tightly packed microcells (20-100 μm diameter) with each microcell acting as an avalanche photodiode that can behave in the geiger mode regime when the device is reverse biased above a threshold voltage (breakdown voltage). The trigger event can be created internally through thermal activation (and thereby acts as a noise source), or be an incoming photon of the right wavelength range and at a given probability determined by the bias above breakdown and the sensor's quantum efficiency. The resultant avalanche is quenched with a polysilicon resistor associated with each microcell. By using such small microcells, the avalanche can be controlled to the point where the gain achieved is very uniform among all the microcells. Furthermore, this gain is on the order of 10^5-10^6, a characteristic usually reserved only for vacuum photomultipliers. Since this gain is uniform and reproducible at a given bias, the microcell acts as a digital device with a single uniform response pulse to an incoming photon. By wiring the microcells in parallel, the number of fired cells can be counted allowing one to use the device as an analog counter of photons. For sufficiently small SiPMs (3x3 mm^2 is typical), the overall noise level is small enough at room temperature to allow one to resolve photon number peaks in charge spectra.

Silicon Photomultiplier Characteristics

SiPMs have several characteristics that are important for their use:

[1] good photon detection efficiency (> 20%) in the visible wavelengths,
[2] high gain (~10^6) equivalent to good vacuum photomultiplier tubes
[3] immunity to magnetic fields,
[4] compact form factor, and
[5] low voltage operation.

Indeed, their magnetic immunity (tested to 7 T or better) is one of the main reasons for their use in GlueX, and will continue to be a major factor in their use in future detector systems for high energy physics which almost always require the use of a strong magnet for charged particle identification. In association with magnetic immunity, their compact form factor is fortunate since modern detector systems need to maintain a tight, compact form to maintain a high efficiency at capturing particles.

There are also some characteristics that have to be dealt with for proper use of the SiPM. Chief among these is the temperature sensitivity. SiPMs have gain curves (linear) that rapidly rise as a function of bias above the breakdown voltage – typically 1-4 V above breakdown is needed to achieve 10^6 gain. However, this breakdown voltage is highly sensitive to temperature. For example, the SiPMs can have the output pulse change by 10% per degree Celsius. Fortunately, this change is well measured, and most importantly, the gain curves have the same slope regardless of the actual breakdown voltage at a given temperature. Thus the device performance can be tightly controlled as long as the temperature is also under control. This is one of the key features of the implementation of SiPMs within the barrel calorimeter of GlueX. The SiPM arrays, besides being of a specific photosensitive area (144 mm^2) needed for the readout, are mounted within a thermally conductive (and magnetically immune) ceramic base so that their temperature can be tightly controlled. Even with the tight control an additional passive bias compensation scheme is implemented for each device in the Gluex detector to assure gain stability with small temperature fluctuations. These features will probably have to be implemented in some form with almost all uses of SiPMs as precision photodetectors. Indeed, it is expected that a further improvement to these devices will be the implementation of onboard temperature sensors (with pinout) as a standard product feature.

Another characteristic (again with high sensitivity to ambient temperature) is that of the dark noise. This is considered to be a key negative characteristic to the widespread implementation of SiPMs. However, the vendors have been highly sensitive to this issue. For GlueX, Hamamatsu has already reduced the dark rate by a substantial factor from the early array prototypes to the present sample set. (Early prototypes had a typical room temperature rate of 500 kHz/mm^2. This has been reduced to about 100 kHz/mm^2.) The dark rate can be also be reduced by operating at a lower temperature. Typically a factor of x2 reduction can be made by lowering the temperature by 10°C.

Radiation Damage

The final concern is that of sensitivity to the radiation background of during beam delivery. A variety of literature on SiPMs [2,3,4,5,6] has already indicated that these devices have a relatively low tolerance to radiation, especially in regard to neutrons or other hadrons. Although PDE (photon detection efficiency) and gain seem to be preserved, the dark noise rises considerably, thereby limiting the low light detection capability of the device. For GlueX, simulations [7] indicate low electromagnetic backgrounds, of the order to a few hundred rads over the expected 10 year lifetime of the experiment. Both the literature and internal experiments [7,8] indicate that the SiPMs will not suffer any damage from electromagnetic backgrounds. However, the expected neutron backgrounds [7,9,10] will have a significant effect. It has been found that 10^9 n/cm^2 (1 MeV equivalent) will raise the dark rate by a factor of x5. This is the limit that can be tolerated for low energy gamma detection efficiency in the barrel calorimeter. Using the original dark rates expected (500 kHz/mm^2), the expected lifetime of the SiPM devices was insufficient - 1-3 years depending upon the target (H or He) and the position of the SiPMs in the calorimeter. The next step is to reduce the operating temperature from room temperature to 5°C.

The dark rate at 5°C is reduced by a factor of x3 allowing the devices to be used throughout the expected 10 year lifetime. In addition, it was found, as in many radiation damage experiments, that there can be dose rate effects. That is, online annealing is too slow to keep up with the rate at which the damaging dose is being delivered. It was found that post-irradiation annealing could be accelerated steeply by raising the temperature to 40-60 °C. So the plan is to have the SiPMs cooled to 5°C during beam operation, thereby minimizing the effect of radiation induced additional noise. To remove the possibly higher levels of damage due to dose rate, the SiPMs will be heated to about 40°C during beam down periods to bring the noise down to a residual (and otherwise permanent) level. In this way, the lifetime of the SiPM photodetectors will be extended to the full 10 years.

Figure 1 shows the typical phenomenon seen in the irradiation tests. Dark current rises as a function of the delivered dose. Due to the dose rate effect, annealing to a smaller residual (and permanent) level of damage occurs at a rate that is strongly termperature dependent. At 25°C, annealing requires at least 5 days. This can be shortened to less than one day if the annealing takes place above 40°C. Other important aspects to be noted is that (a) the additional dark rate increase is not dependent upon previous dose, (b) the additional damage is independent of previous annealing conditions, and (c) the final residual level of damage rises linearly with dose.

It should be noted that this prescription was based on the tests of the earlier (and much more noisier by x4-x5) prototype arrays. Since the newer production samples are showing an high degree of improvement, it is likely that the expected lifetime will be much longer than originally anticipated. Radiation tolerance tests are planned for the new samples to verify this expectation.

Electron Ion Collider Application

In any case, it is clear that SiPMs are a relatively radiation soft device, especially in hadron rich backgrounds. The creation of sites such as a future Electron Ion Collider (EIC) will only increase the problem [11]. Given the needs of the envisioned detector systems [11] with regard to acceptance coverage and spatial configurations, it seems only natural that a compact, highly photosensitive (and high gain), magnetically immune photodetector would find use in such EIC detector systems. That being the case, it is imperative that work in improved radiation-hardened SiPMs be carried out not only for the proposed EIC systems, but as a generic improvement.

Specific Aims

In this regard, Hamamatsu has already approached JLAB/GlueX on the issue of testing possibly more radiation tolerant SiPMs. They have been aware of the radiation damage issues for some time now, and have been formulating some new variations worthy of trial but have no means to deliver controlled doses and testing performance characteristics with the an appropriate test setup. To facilitate the development of improved radiation tolerant SiPMs we are proposing the following specific aims to be accomplished over a period of one year. We anticipate towards the end of this study we will be better prepared to propose further studies to continue to improve this technology for nuclear physics applications.

Specific Aim 1

Obtain 5 to 10 SiPM samples from Hamamatsu in which manufacturing parameters have been varied and then perform a standard set of bench testing to obtain and compare performance characteristics to earlier versions

Specific Aim 2

Irradiate SiPM samples during a series of experiments under various starting conditions such as pre-annealing, bias voltage applied, bias voltage not applied.

Specific Aim 3

Repeat a standard set of bench tests, generate reports and in collaboration with Hamamatsu chart further possible modifications.

Test Setups

There are two benchtop setups for characterizing the performance of the SiPMs. The first one is shown in Figure 2. This has been developed for full characterization of any test sample SiPM. This includes PDE, dark rate, crosstalk and afterpulsing (from delayed avalanches). The setup has been designed to be flexible and modular. There are also slight modifications of the test setup designed to (a) measure the absolute photon flux, and (b) measure the dark current through the SiPM. This setup can be used for full characterization of the SiPM before and after irradiation, as well as during any annealing period.

Figures 3-5 are photographs of the setup used in direct testing of the irradiated SiPMs for the GlueX tests. Some combination of the two setups is intended for use in future irradiation tests. Modifications may be implemented as needed.

Budget Justification

It has been our experience that creating new versions of SiPMs is an inherently expensive process, so we are proposing Hamamatsu be provided some funds in order to (a) compensate them, to some extent, for the cost of producing these new variations, and (b) use the funding to stimulate new research and development in the SiPM field.

We propose $40K as funds for this proposal. Of this $35K is expected to be used as reimbursement for some of Hamamatsu's costs in developing these new radiation-tolerant devices. The remaining $5K would be used for modifications or improvements to the present test setups to cover shop, engineering and supplies costs. JLab would contribute normal operational funds to carry out the tests since these are of interest to GlueX in any case as well as to the nuclear and particle physics community.

Key Personnel

The Radiation Detector and Imaging Group in the Physics Division of Jefferson Lab is a team of seven researchers, comprising four Ph.D scientists, a mechanical engineer, an electrical engineer and a software developer. The Detector Group is a core capability of the Thomas Jefferson National Accelerator Facility in Newport News, Virginia.

Carl Zorn, Ph.D., Principal Investigator: (25% of FTE) is a Staff Scientist in the Radiation Detector and Imaging Group. He has over 20 years experience in the area of scintillator implementation research and photon detection technology. He developed a beam monitoring system based on PSPMTs and is the Jefferson Lab expert in the evaluation and use of silicon photomultipliers (SiPM). He will be dedicating 25% of his time to the effort and will oversee the complete technical aspects of the project.

Andrew Weisenberger, Ph.D., Co-Investigator, (5% FTE), is Group Leader for the Radiation Detector and Imaging Group in the Department of Physics at Jefferson Lab. He has over 15 years experience in the area of detector instrumentation development and data acquisition system design. He will insure the lab resources are available to the project and coordinate contract details between the Detector Group and Hamamatsu Corporation.

Jack McKisson, MSEE, Electrical Engineer, (10% FTE) is chief electrical engineer for the group. He has over 20 years experience in detector electronics (analog and digital) design and construction. He is presently responsible for the electronics design for the temperature stabilization system for the GlueX SiPMs. He will be responsible for the development of analog and digital electronics to facilitate the SiPM testing.

Jefferson Lab Resources

The JLab Physics Division has three instrumentation development groups: 1) the Radiation Detector and Imaging Group, 2) the Fast Electronics Group and 3) the Data Acquisition Group. These have scientists, engineers and technicians who possess core competencies in several technical areas useful for supporting nuclear physics research. The three groups have expertise in several areas relevant to radiation detector development and testing, including: 1) component technologies of pixellated scintillators, position-sensitive photomultiplier tubes, solid state detectors and light guides; 2) fast analog and digital detector readout electronics design and construction; 3) software development for real-time computer-controlled data acquisition.

Jefferson Lab has all the necessary facilities, tools, computer workstations and expertise to design, construct and perform laboratory evaluations of the detector systems. In addition to open laboratory areas and tools available to the general research personnel at Jefferson Lab, the Detector Group has two laboratory work areas available to it exclusively on the Jefferson Lab campus. One 1600 ft^2 lab is in the Experimental Equipment Laboratory (EEL) and the second is a 300 ft^2 lab in the Jefferson Advance Research Center (ARC). Both facilities are on the Jefferson Lab campus. Within these labs there are various pieces of equipment and tools necessary for detector development and testing. These items include radioactive calibration sources, digital and analog oscilloscopes, dark boxes for photon-detector and scintillator testing, high voltage supplies, several computer workstations interfaced to PCI, CAMAC, VME based and FPGA Jefferson Lab developed USB2 analog to digital electronics**.**

JLab has already performed a variety of radiation tests of SiPMs [7,8,9,10] and has both gamma (^{137}Cs, ^{60}Co) and neutron (AmBe) sources for controlled tests. Although controlled tests are difficult in the experimental halls, high rate gamma/neutron irradiations are also possible (and have been done [9,10]) in one or more of the three current experimental halls.

Timeline

Months	1 2	3 4	5 6	7 8	9 10	11 12
Define SiPM sample parameter	o--x					
Order SiPM samples	o--x	----	----	----	----	---x
Test SiPM pre-irradiation			o--x			
Irradiate samples and monitor characteristics			o---	----x		
Final measurements post irradiation					o---	---x
Prepare technical report						o--x

o - Task startup
x - Task complete

Figures

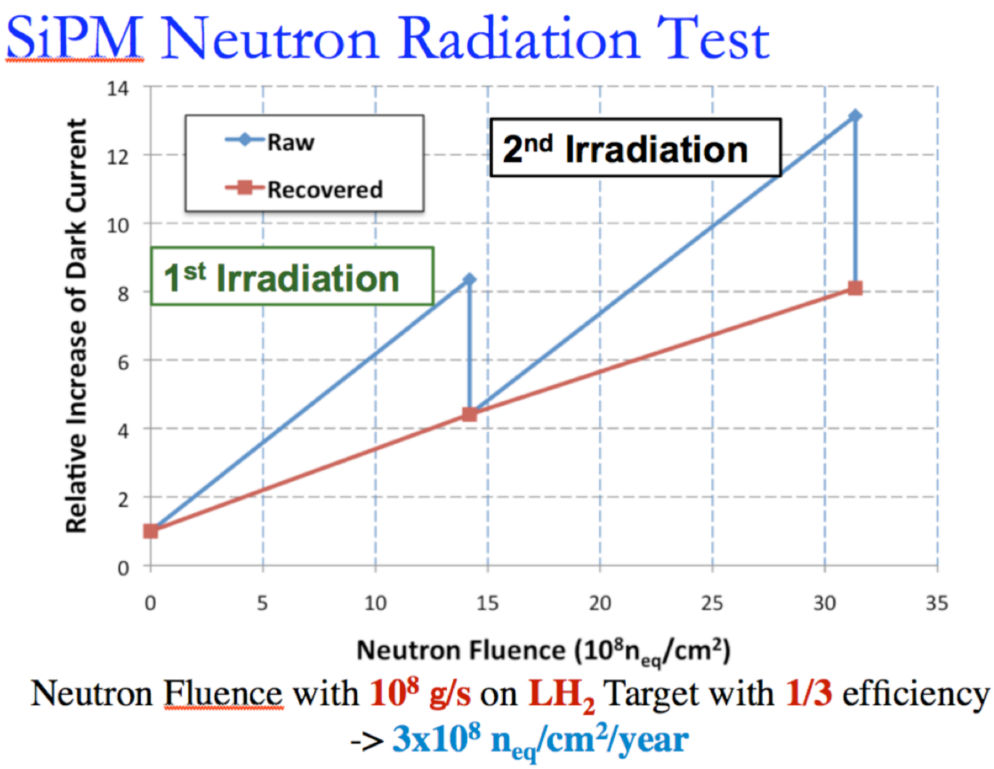


Figure 1: Typical effect of neutron irradiation upon SiPM dark rate. The blue lines show the increase during irradiation. After irradiation, the dark rate recovers to a permanent residual level shown in the red lines. The annealing time is strongly temperature dependent. Heating to above 40°C can reduce the annealing time to less than 24 hours.

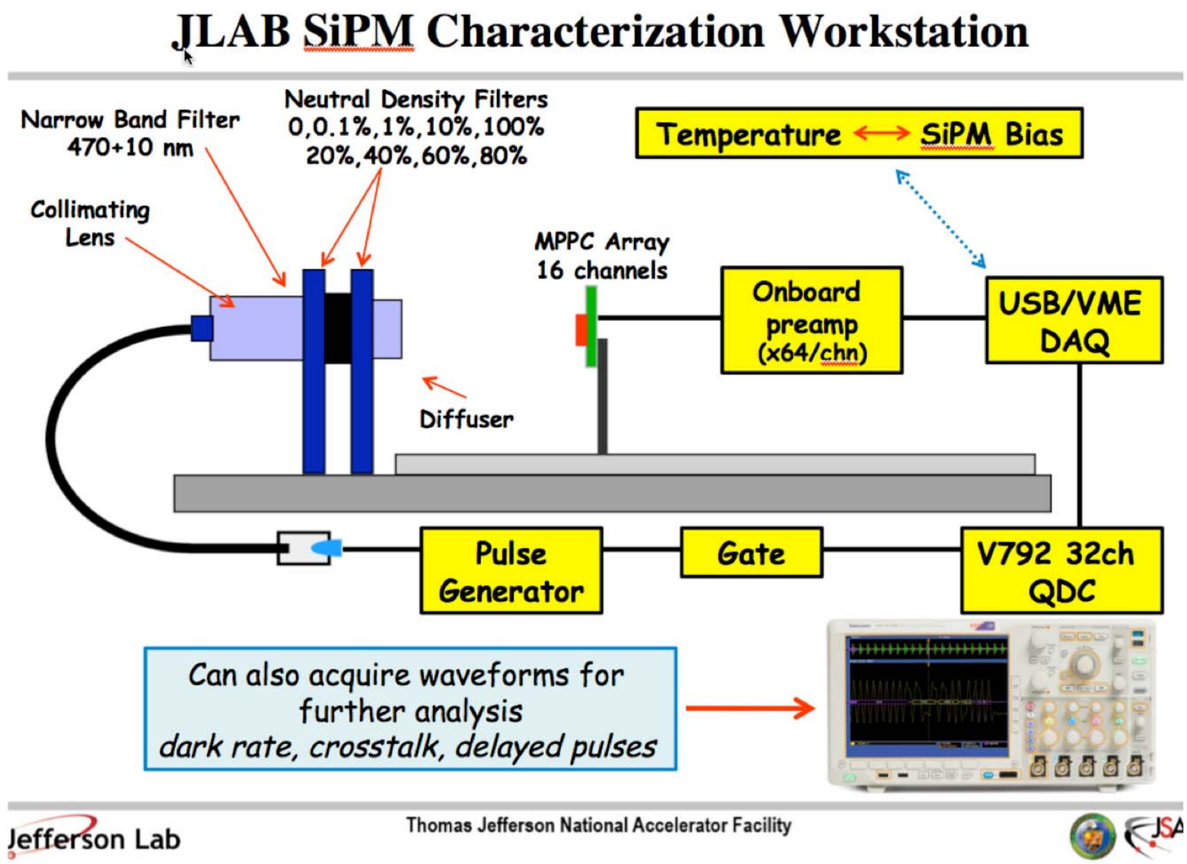


Figure 2: Present SiPM characterization test setup. The setup is flexible and modular. There is a modified version designed to measure the absolute photon flux and another to measure the dark current of the SiPM. This can be used to characterize the test samples before and after irradiations.

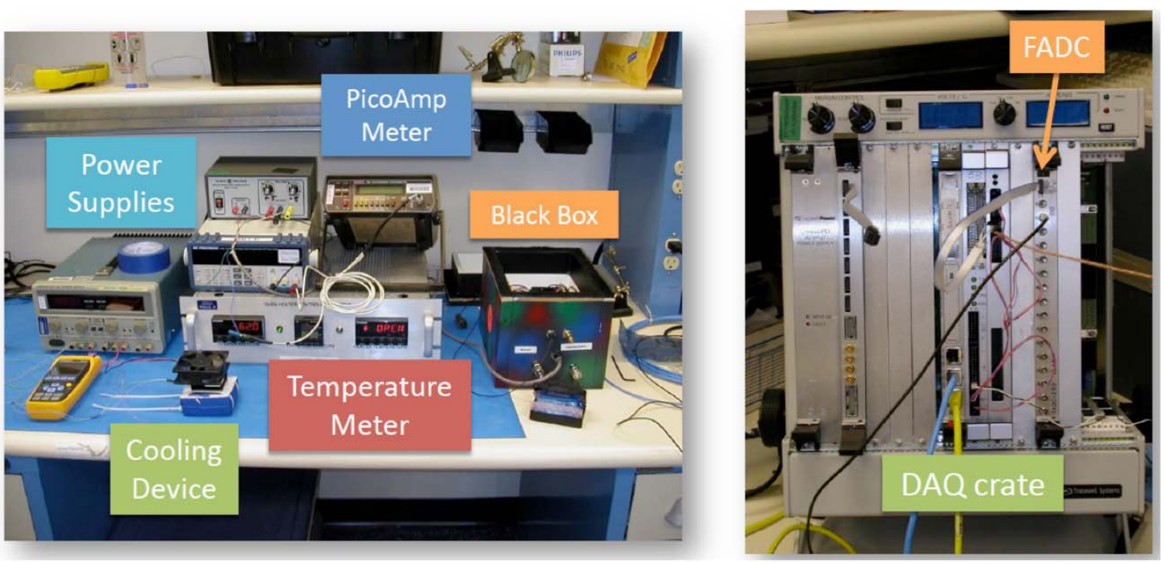


Figure 3: Present setup for irradiation tests of SiPMs. Some combination of the setups in Figures 1 and 2 will be used for the proposed tests.

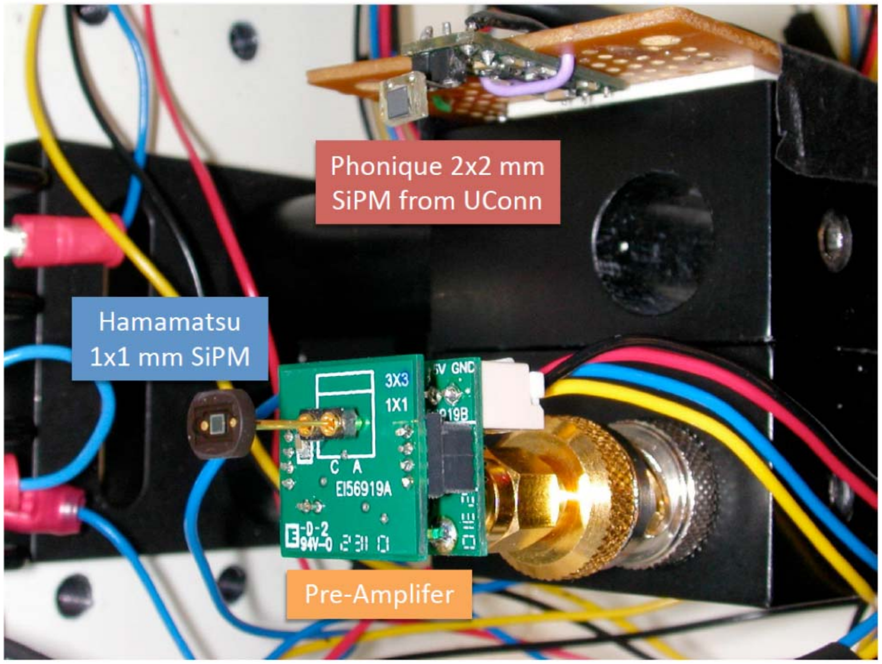


Figure 4: Closeup of test samples in the portable dark box used in the GlueX irradiation tests

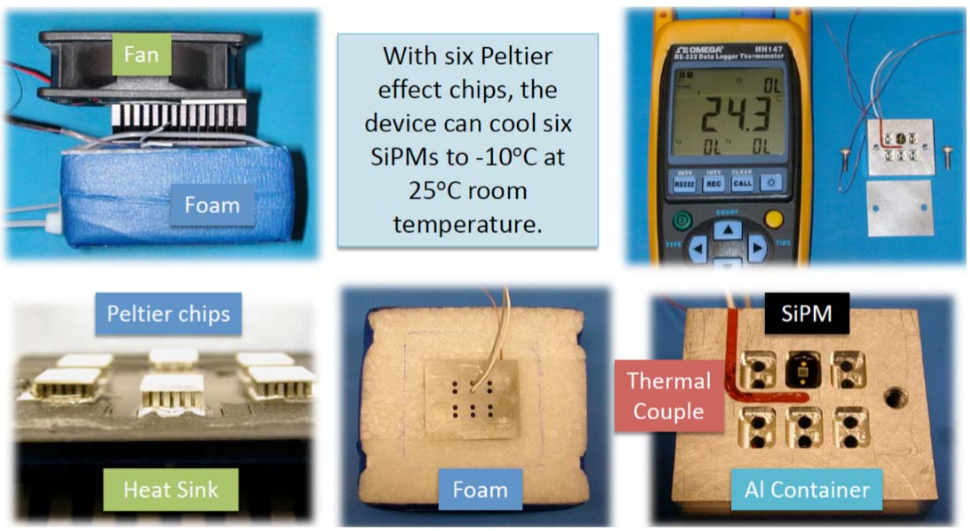


Figure 5: Photographs of the Peltier-based temperature control setup used to both monitor and set the temperature of the SiPM samples during and after irradiation.

References:

[1] D. Renker, E. Lorenz, "Advances in solid state photon detectors," JINST 4 (2009) P04004.

[2] T. Matsumura et al., "Effects of radiation damage caused by proton irradiation on Multi-Pixel Photon Counters (MPPCs)", Nucl. Instr. Meth. A603 (2009) 301-308.

[3] S. Sanchez Majos et al., "Noise and radiation damage in silicon photomultipliers exposed to electromagnetic and hadronic radiation", Nucl. Instr. Meth. A602 (2009) 506-510.

[4] M. Angelone et al., "Silicon Photo-Multiplier radiation hardness tests with a beam controlled neutron source", Nucl, Instr. Meth. A623 (2010) 92-926.

[5] I. Nakamura, "Radiation damage of pixelated photon detector by neutron irradiation", Nucl. Instr. Meth. A610 (2009) 110-113.

[6] T.Matsubara et al.,"Radiation damage of MPPC by gamma ray irradiation with ^{60}Co", Proceedings of the International Workshop of New Photon-Detectors (PD07), (Kobe University, Kobe, Japan, June27–29) 2007 (PoS(PD07) 032).

[7] P. Degtiarenko et al., "Calculation of Radiation Damage to Silicon Photomultipliers in GlueX Experiment", internal document (GlueX-doc-1660, Feb. 2011).

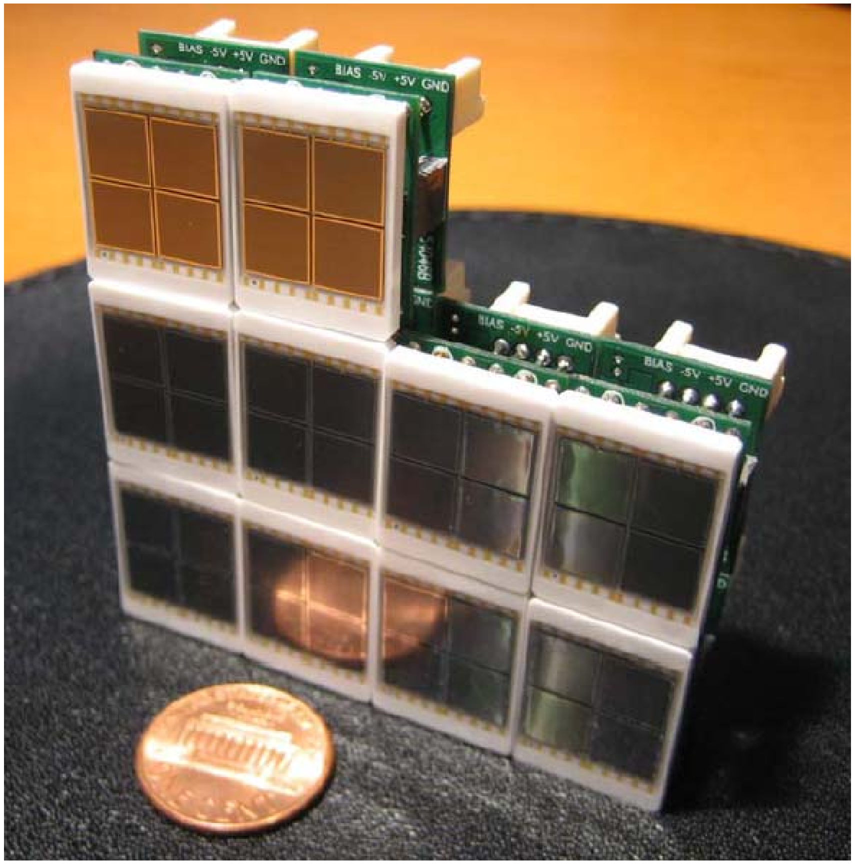
[8] C. Zorn, "MPPC Irradiation", internal document (GlueX-doc-1393, Jan. 2010).

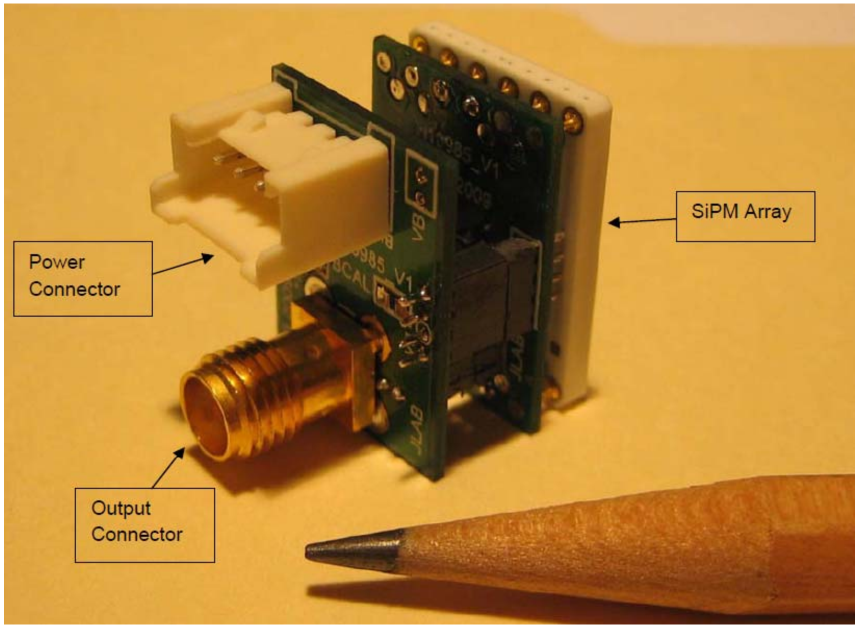
[9] Neutron irradiation tests and setups described at this link.
(http://www.jlab.org/Hall-D/software/wiki/index.php/SiPM_Radiation_Hardness_Test)

[10] Y. Qiang, "Report on radiation hardness of SiPMs," internal document (GlueX-doc-1583).

[11] EIC Detector Workshop at Jefferson Lab, June 4-5, 2010 – link here
(http://conferences.jlab.org/eic2010/program.html)

Gamma Irradiation of Hamamatsu MPPC Array





Carl Zorn

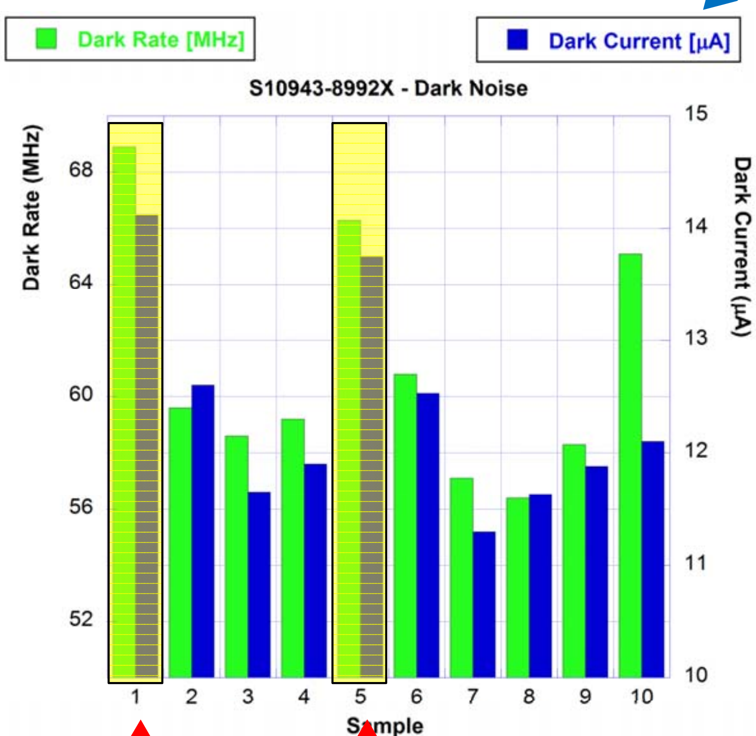
JLAB Radiation Detector

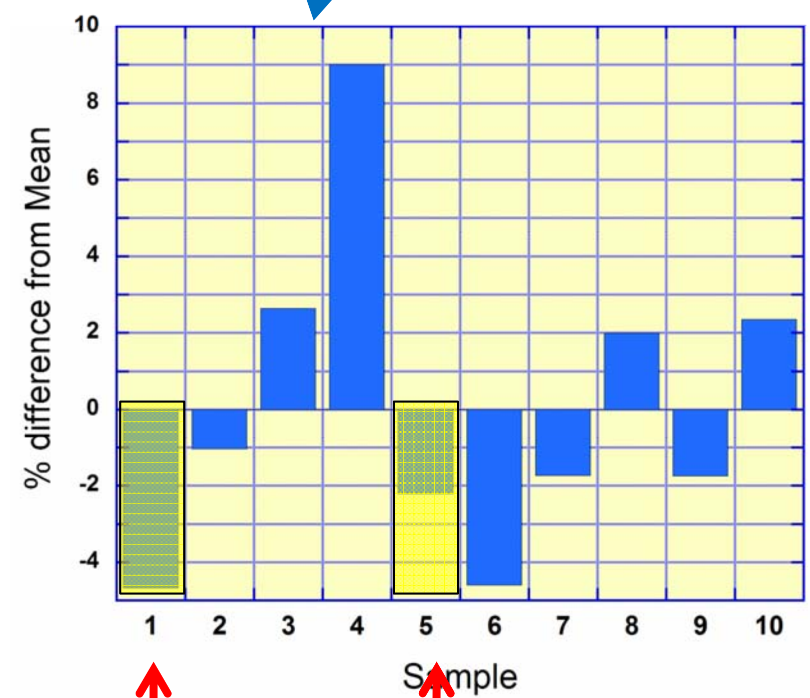
& Medical Imaging Group

Monday, January 4, 2010

Setup

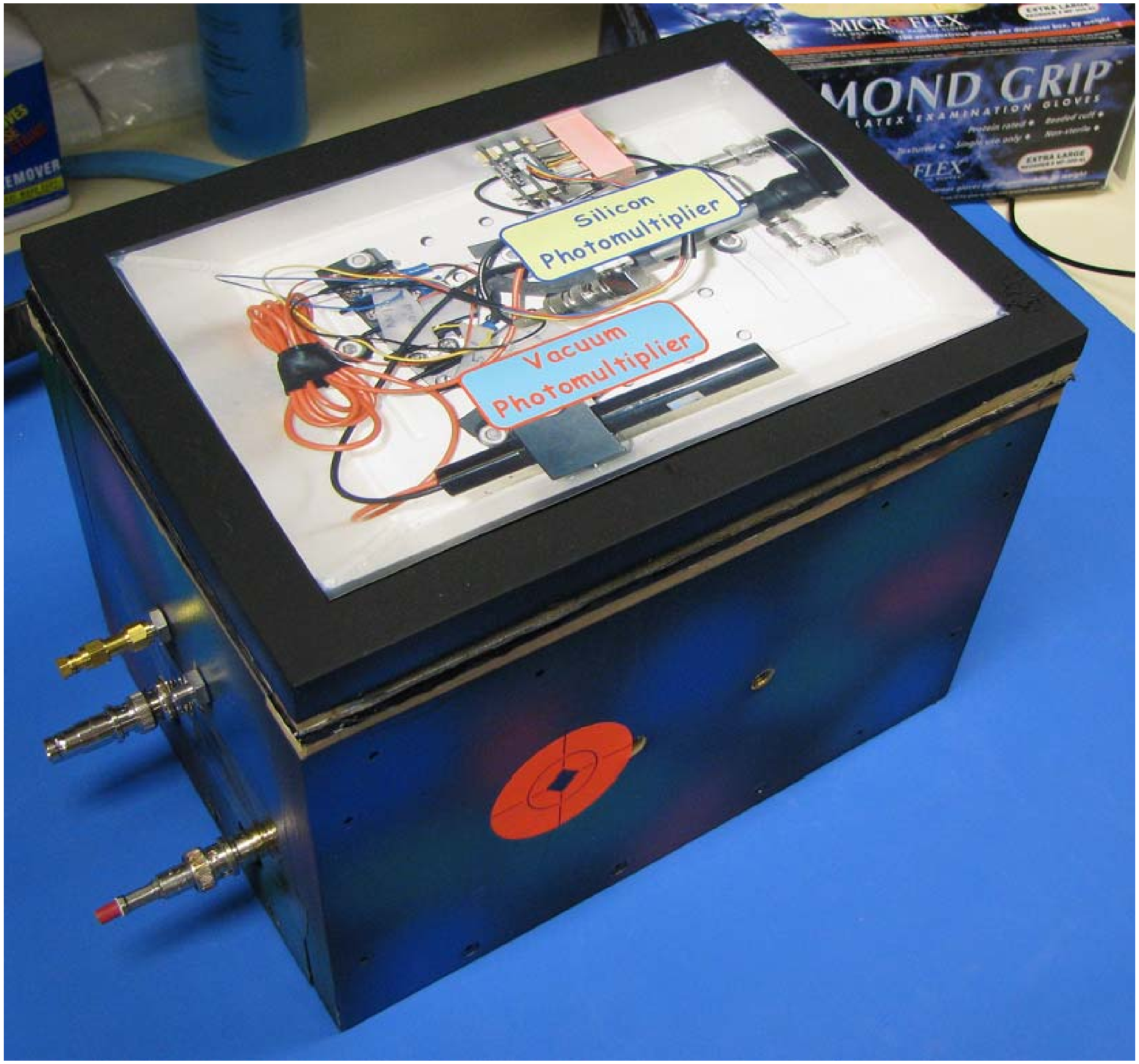
- Choose two samples – one as reference (#5) and the other (#1) for irradiation
- Samples have similar noise and output amplitudes



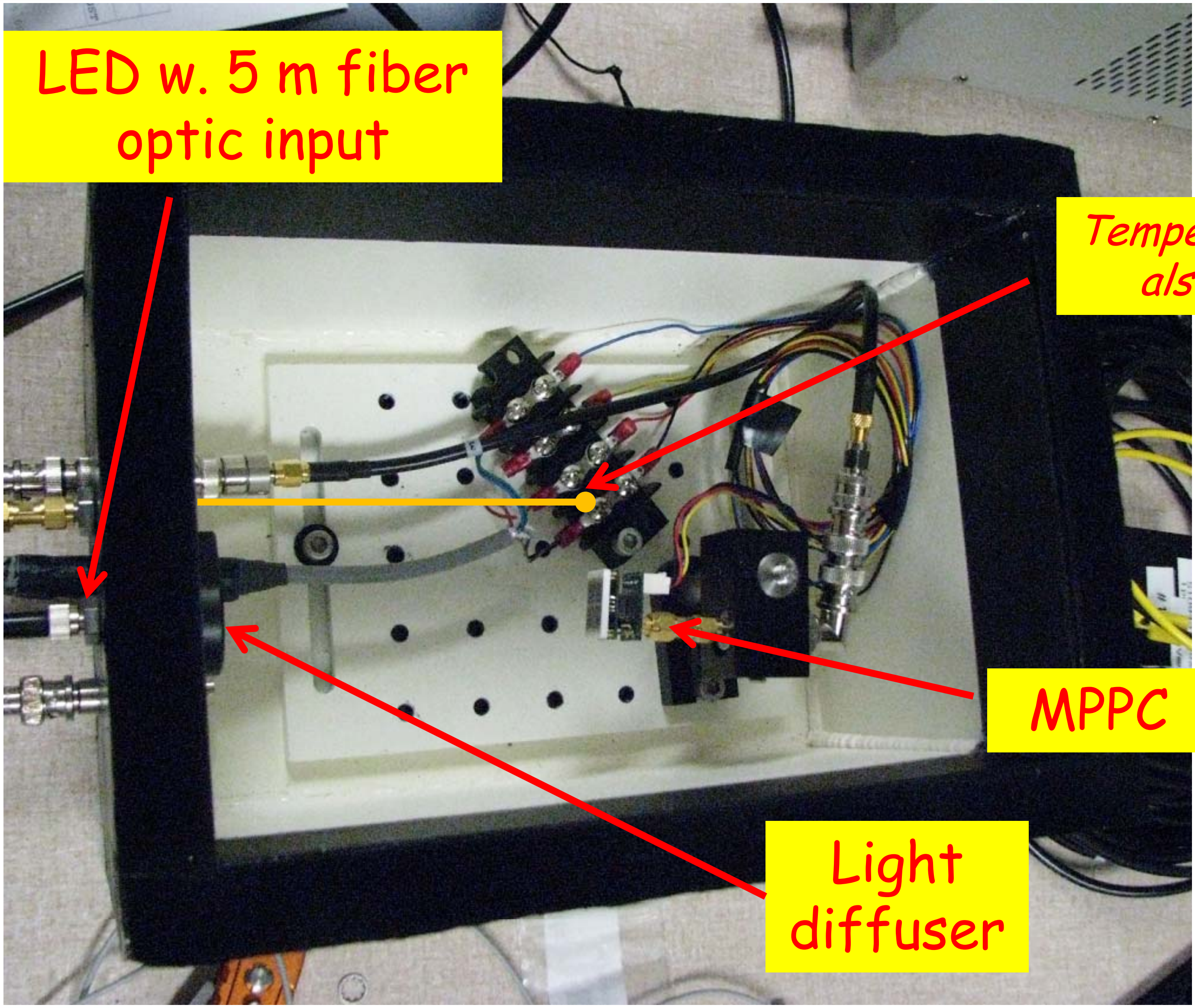


Jefferson Lab

Sample Dark Box for Irradiation



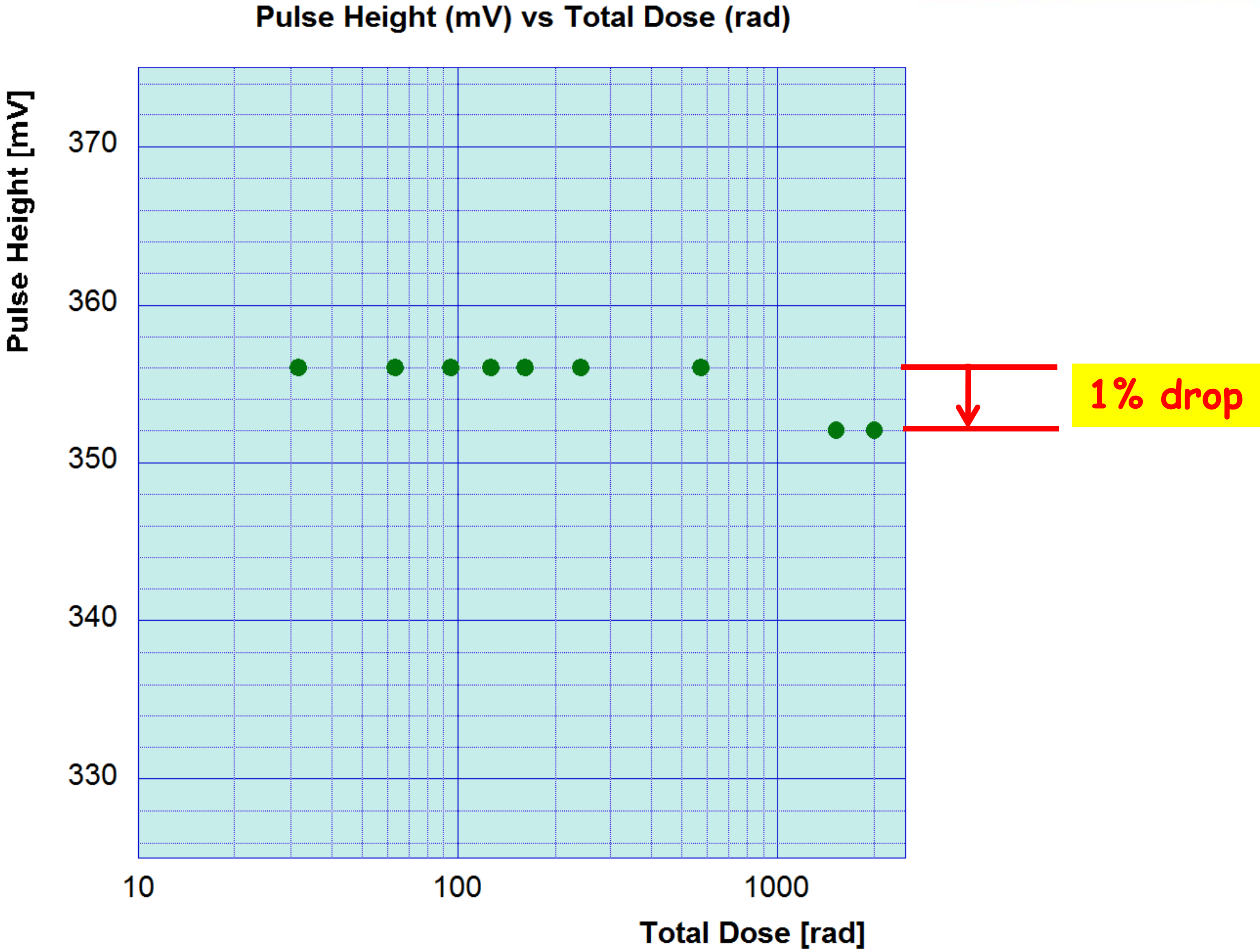
Inside Sample Box



Irradiation Setup

- Use RADCON's Eberline 1000B gamma calibrator – series of high activity Cs-137 (662 keV) sources - Used by RADCON for instrument calibration
- Dose rates determined with RADCAL 1515 with 10x5-60 ion chamber probe (circular) – gives average rate over 60 cc volume (≈ 9 cm diameter)
- Estimate 5% error in dose – worst case
- Irradiated sample powered ON at all times
- Monitor Dark Current, Pulse Height and Temperature (the latter for Vop compensation)
- Use small doses (40 rad) initially to 200 rad – then proceed by larger doses up to 2 krad total
- After final dose – measure charge amplitude and pedestal widths relative to non-irradiated sample

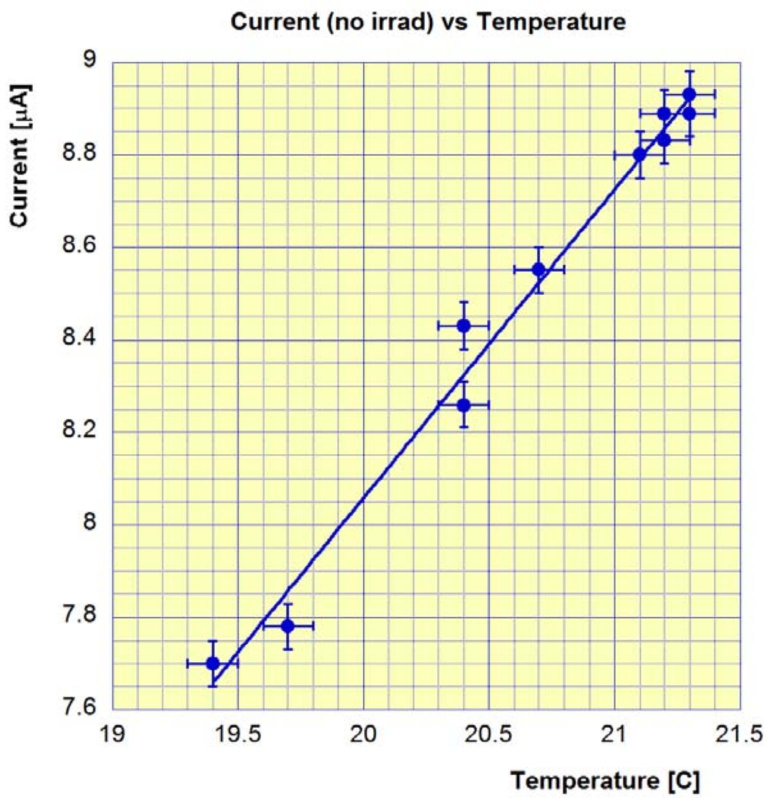
Monitor Pulse Amplitude

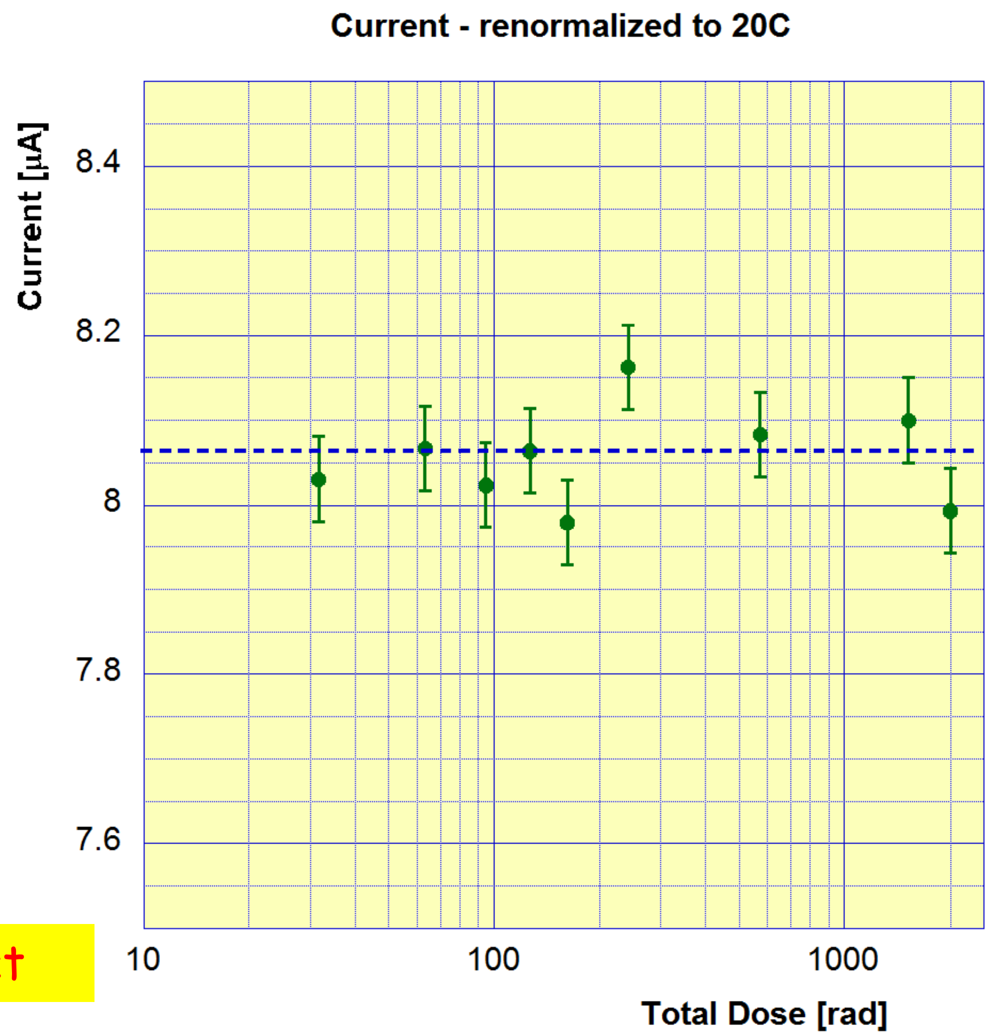


Monitor Dark Current

- Dark Current varies with temperature
- Plot Current vs Temperature – use linear fit
- Use fit to renormalize Current to expected value @ 20°C
- Plot expected values vs Total Dose
- No significant change observed

Monitor Dark Current





No discernible effect

Test Relative Response

- Test irradiated sample relative to Reference
- Compare relative pedestal widths and charge amplitudes
- Again – no discernible change

Up to 2krads gamma irradiation

No significant change in performance of MPPC array

Jefferson Lab

REPORT ON RADIATION HARDNESS STUDY OF HAMAMATSU SIPM

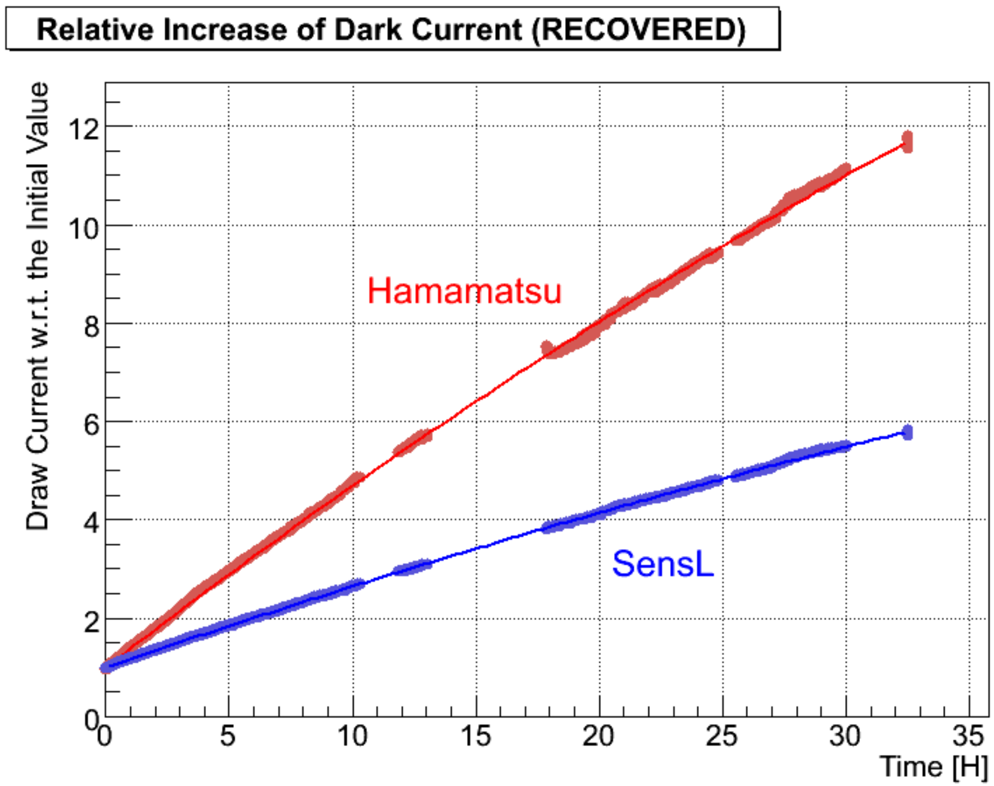
Yi Qiang
Jefferson Lab

Review of Last Meeting

- Neutron brings the greatest damage to Silicon detectors through **N**on **I**onizing **E**nergy **L**oss (**NIEL**).
- A special measurement of neutron radiation hardness was performed during PREx in Hall A with 1 GeV electron incident on a 0.5 mm lead target (9% R.L.).
- Two *4x4 array of 3x3 mm* SiPM samples, one from Hamamatsu and one from SensL, were tested.
- Neutron dose was monitored using a BF_3 probe.
- A Hamamatsu *1x1 mm* SiPM was irradiated later.

Test Results of 3x3 mm SiPMs from Hall A

- Dark current linearly increase as dose accumulated.
- Powering the units or not make no difference.



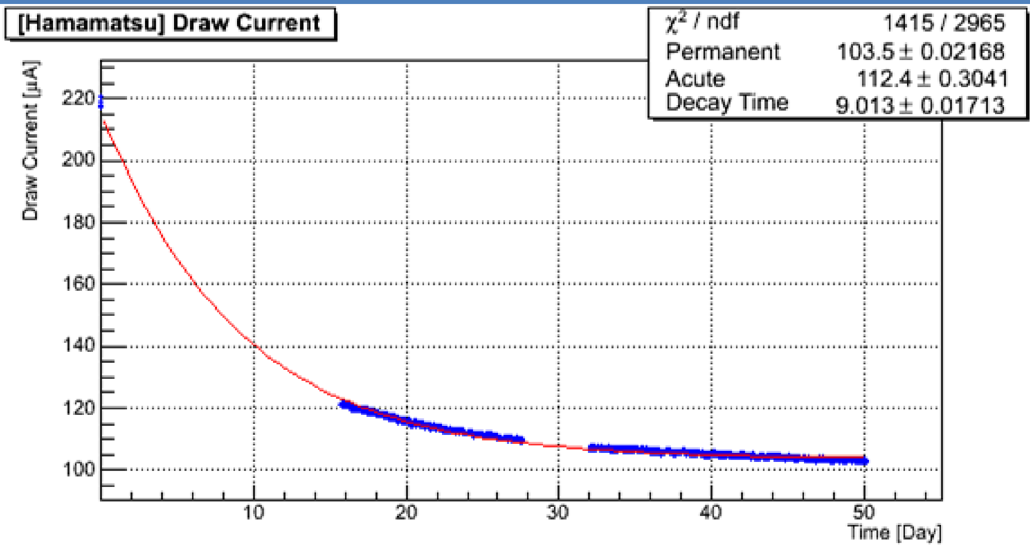
- Gain and PDE not degrading much: < 20% total

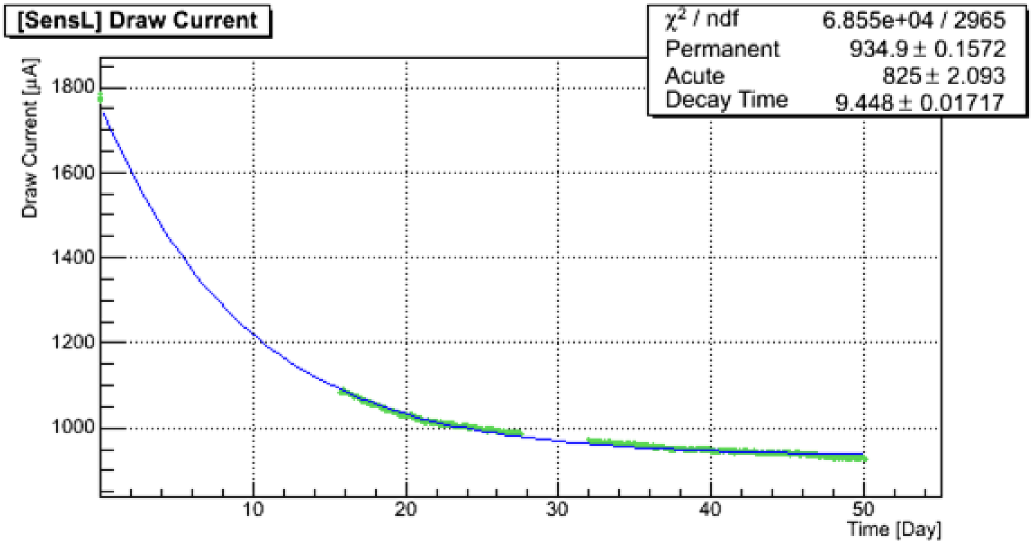
Recovery of Radiation Damage

- 55% of the damage recovered at 23°C with τ = **10** days

$$I = I_p + I_a e^{-t/\tau}$$

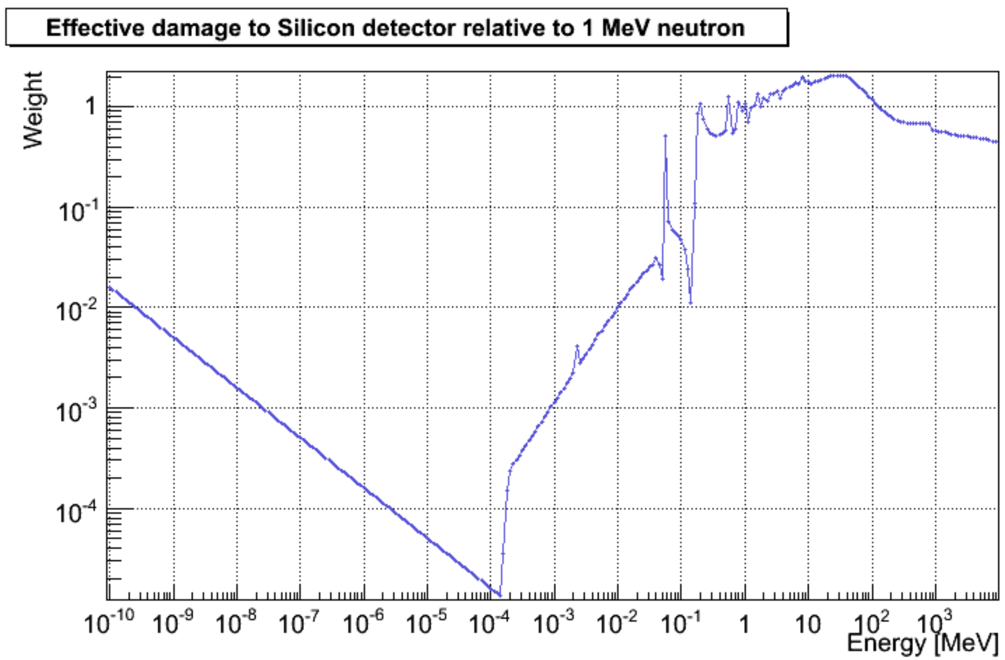
- Gain and PDE fully recovered.





How to Get Life Time in Hall D?

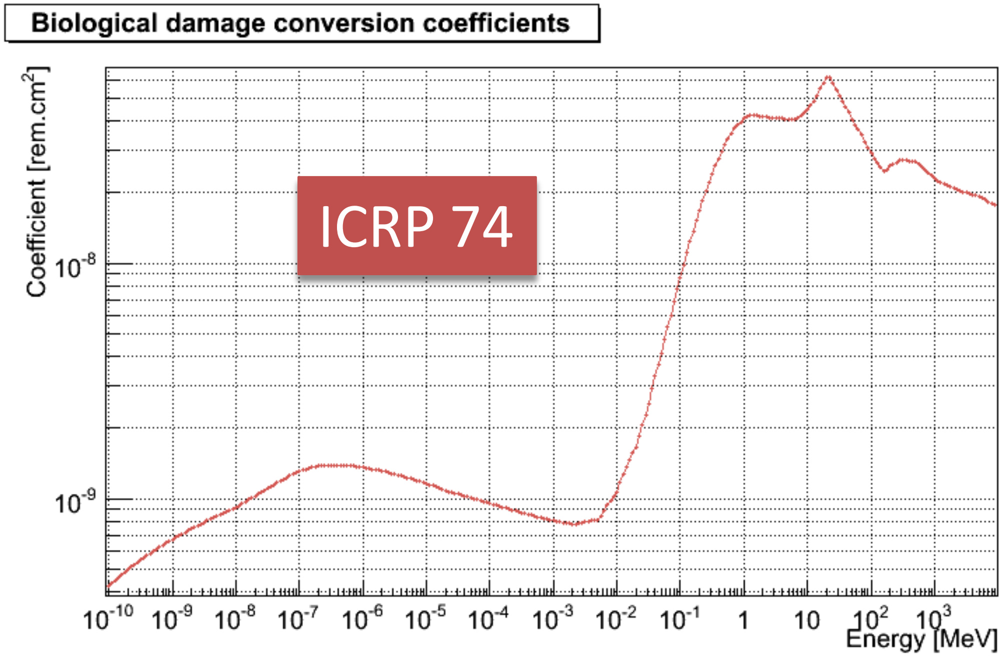
- **Pavel Degtiarenko** did neutron flux simulation for both Hall D and Hall A using his specially tweaked GEANT3 program.
- Convert flux to the damage to Silicon detectors using **NIEL** curve: ***1 MeV equivalent neutron fluence***.



- Compare Hall D fluence to Hall A to get life time.

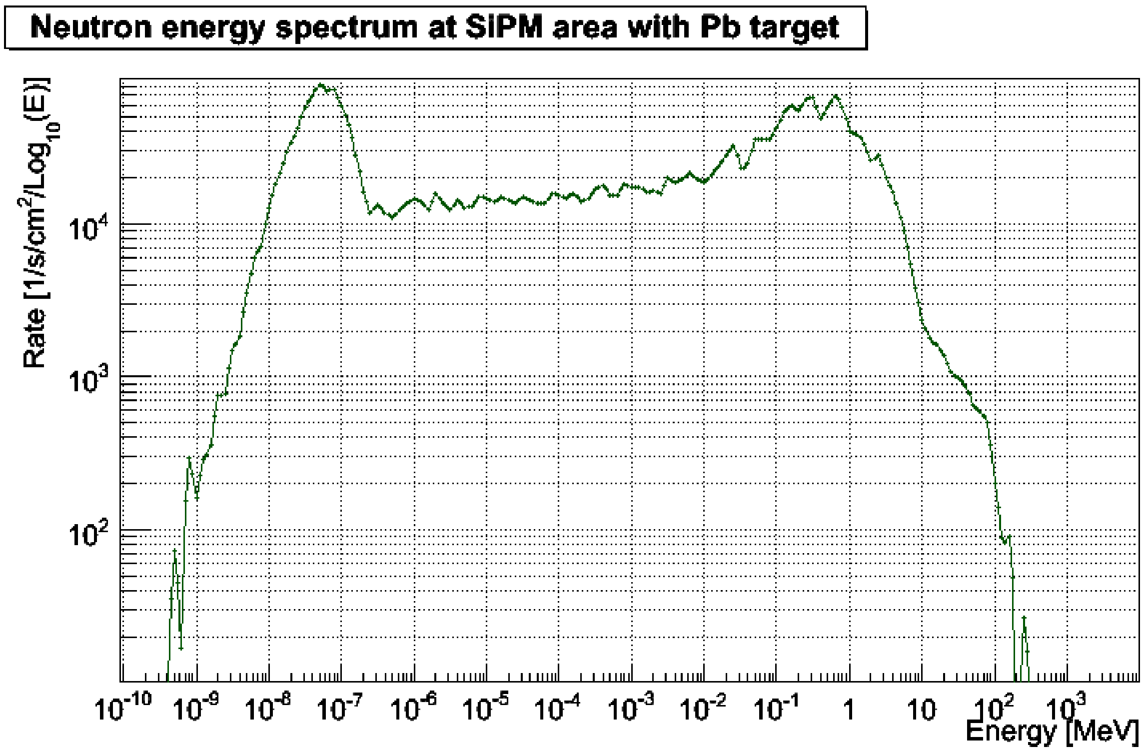
Test of GEANT Simulation

- The neutron flux in Hall A was measured as **dose** in the unit of ***rem*** which is weighted by the biological damage:



- BF_3 not sensitive to high energy neutron (> 20 MeV).
- A calibration then followed by using the RadCon AmBe source.

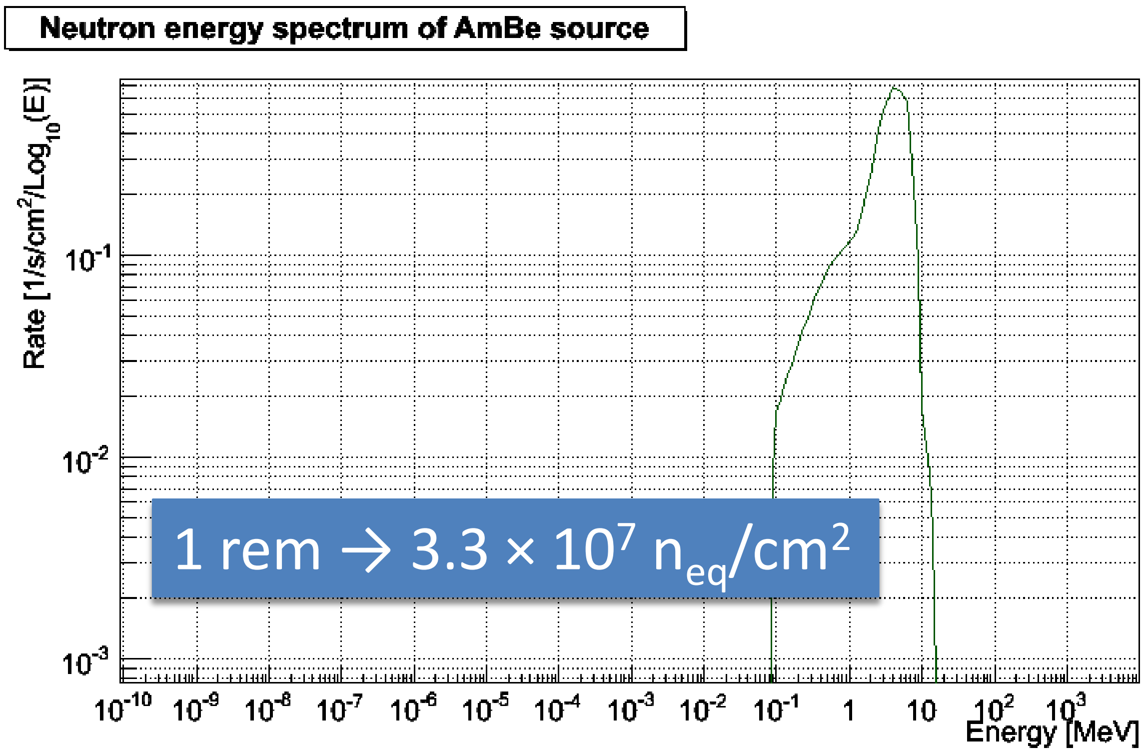
Simulation of Hall A Neutron Flux



- Dose rate: 3.1 rem/H
- Conversion to fluence: 1 rem → 2.4×10^7 n_{eq}/cm^2

Calibration of BF_3 Neutron Probe

- RadCon's AmBe neutron source has well known dose rate: 0.45 rem/H @ 17 cm.
- One 1x1 mm and one 3x3 mm SiPMs irradiated to **32 rem**



1 rem → $3.3 \times 10^7\ n_{eq}/cm^2$

Results of 1x1 mm SiPM

- Increase of dark current: **4**
- ADC spectra with 200 ns gate.
- Dark rate extracted through fits:

$$P(n|\mu,\Delta\mu) = Poisson(i|\mu) \otimes Poisson(j|i\cdot\Delta\mu)$$

$$= \sum_{i=0}^{n} Poisson(i|\mu)\cdot Poisson(n-i|i\cdot\Delta\mu)$$

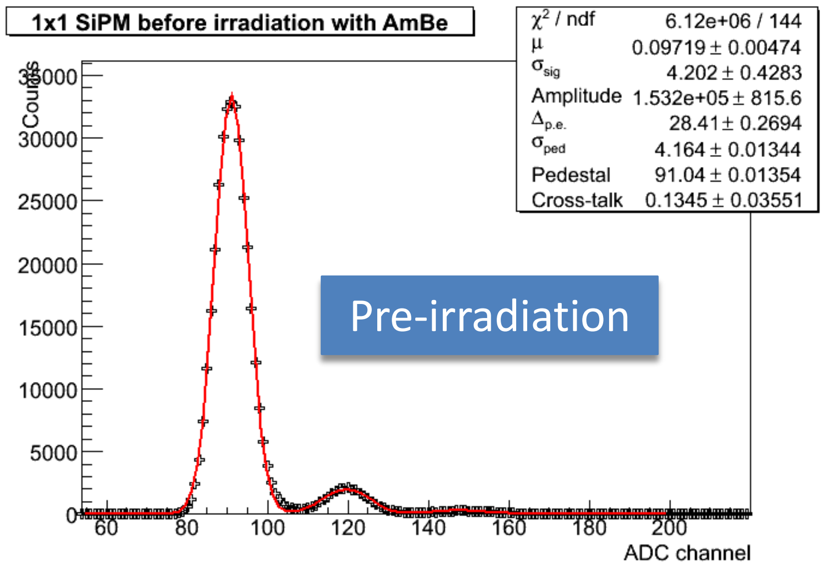
$$= \sum_{i=0}^{n} \frac{e^{-(\mu+i\Delta\mu)}\mu^i \Delta\mu^{n-i}}{i!(n-i)!}$$

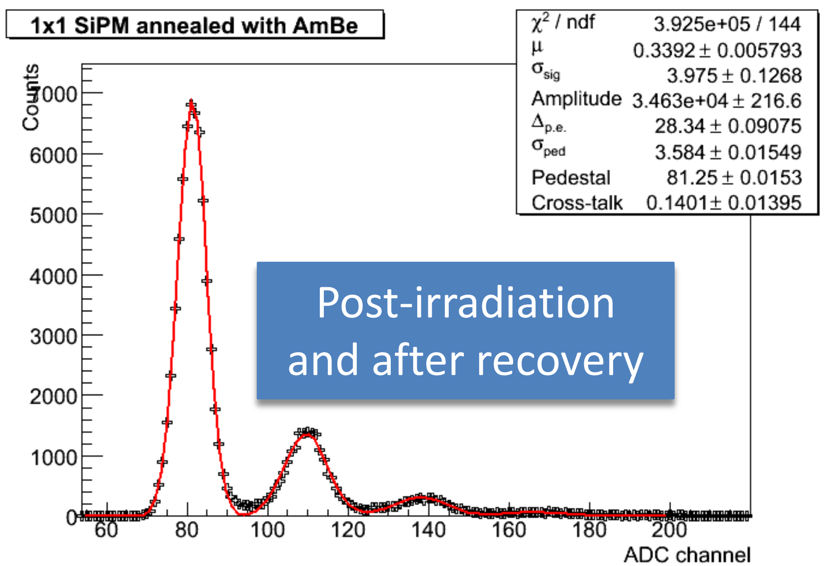
$$\sigma_n = \sqrt{\sigma_{ped}^2 + n\cdot\sigma_{sig}^2}$$

μ = average number of dark pulses in the ADC window
Δμ = probability of cross-talk
σ = width of individual peaks

- Increase of dark rate: **3.5**
  - Consistent with dark current.
- Cross talk: **13%**

ADC spectra measured by Carl Zorn

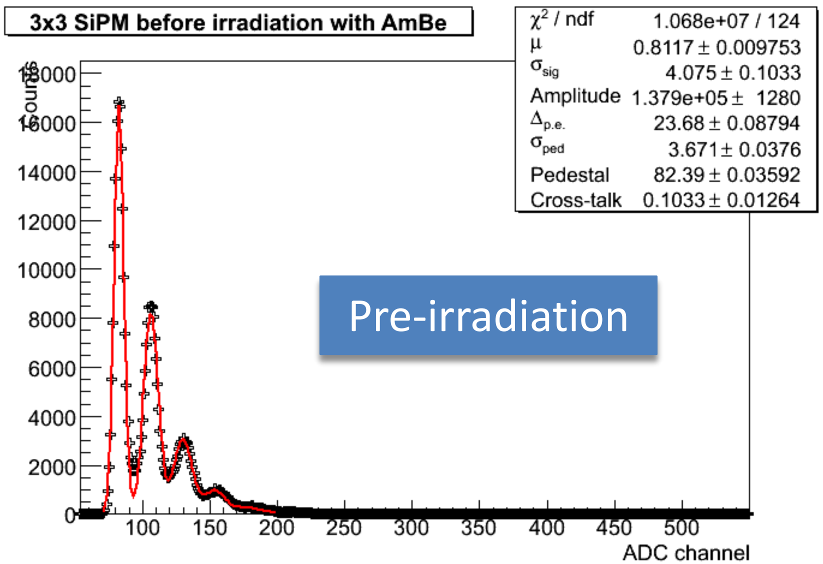


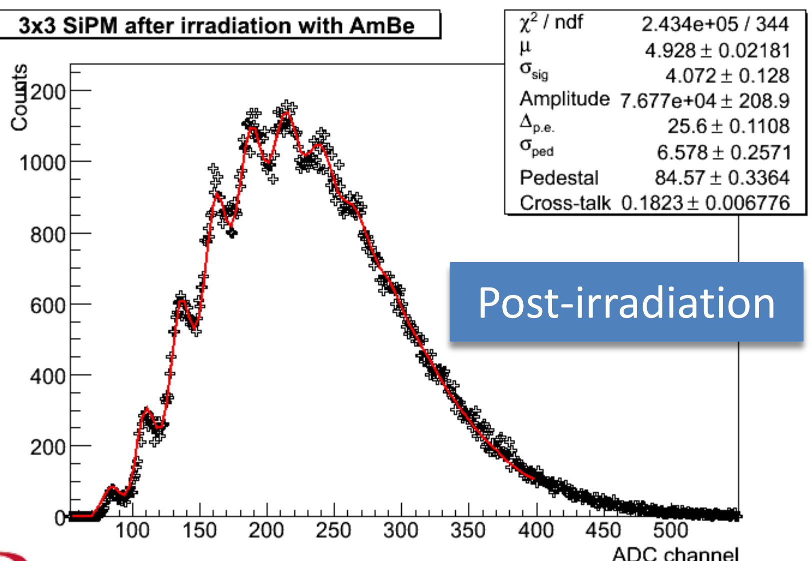


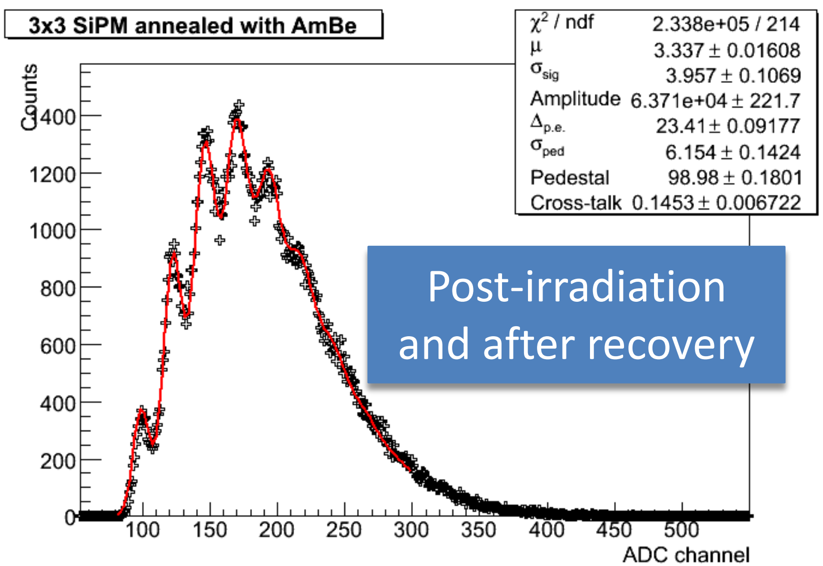
Results of 3x3 mm SiPM

ADC spectra measured by Carl Zorn

- Accumulated dose: **32 rem**
- Increase of dark current: **4.7**
- Increase of dark rate: **4.1**
- Cross talk: **14%**
- Consistent with 1x1 mm SiPM





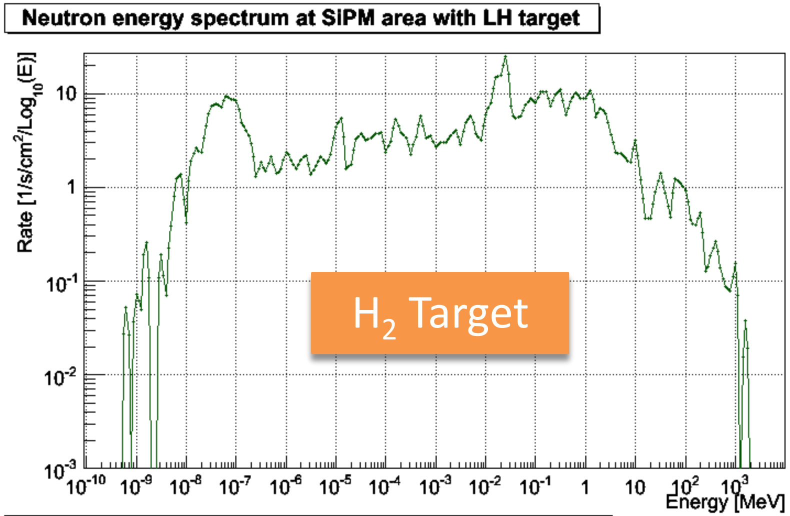


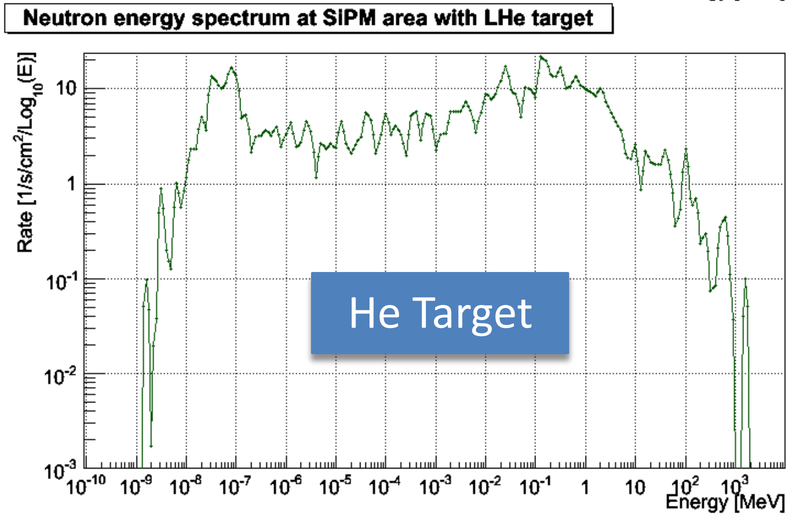
BF_3 Probe Calibration Constant

- With AmBe Source:
  - 32 rem → increase dark current by a factor of 4.4
  - 32 rem → 1.06×10^9 n_{eq}/cm^2
- In Hall A:
  - Increase of 4.4 → 12 rem (measured by BF_3)
  - 12 rem → 2.9×10^8 n_{eq}/cm^2
- Correction factor: **3.6**
  - $1.06 \times 10^9 / 2.9 \times 10^8 = 3.6$
- Hall A dose rate 1.3 rem/H (raw) → **4.7 rem/H**
  - Now consistent with **3.1 rem/H** from simulation.

Life Time of SiPM in Hall D

- Current margin for the increase of dark rate: factor of **5**.
- Dose simulated in Hall A:
  - 34 rem → 8.2×10^8 n_{eq}/cm^2
- Rates through downstream BCal SiPMs in Hall D with 10^8 γ/s:
  - H_2: 4.3 – 3.3 mrem/H
  - He: 6.5 – 4.9 mrem/H
- Life time for 100% efficiency:
  - H_2: 0.9 – 1.1 years
  - He: 0.6 – 0.8 years
- Upstream rates are 4 times lower.





1 rem → 2.6×10^7 n_{eq}/cm^2

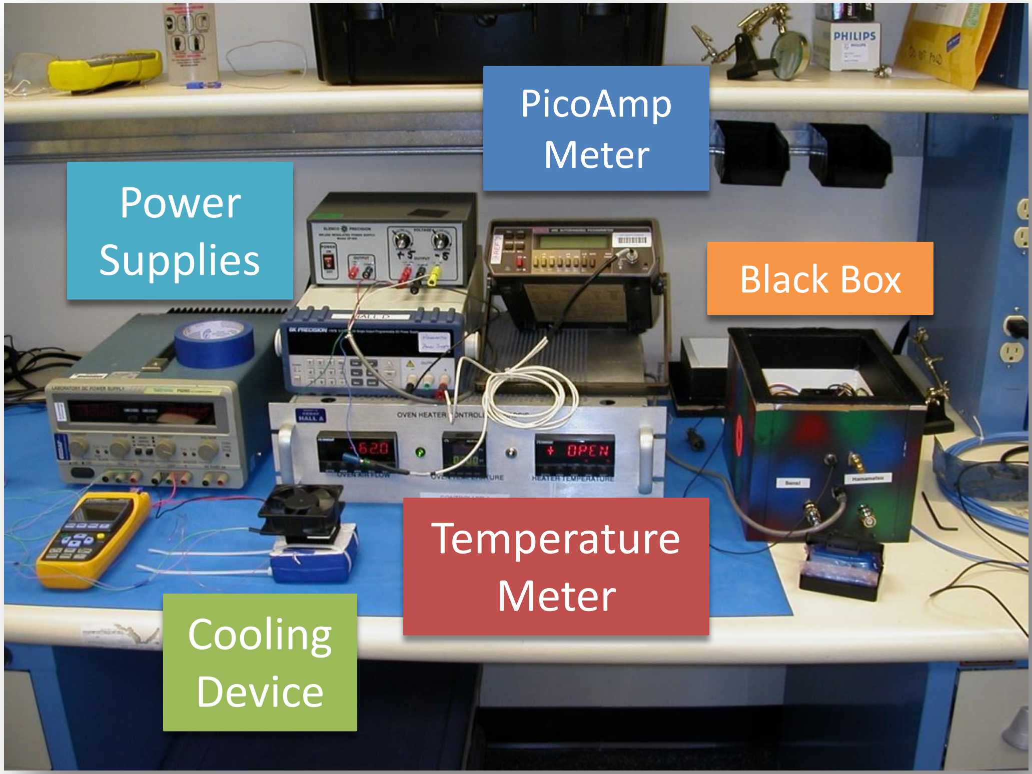
Factors to Extend Life Time

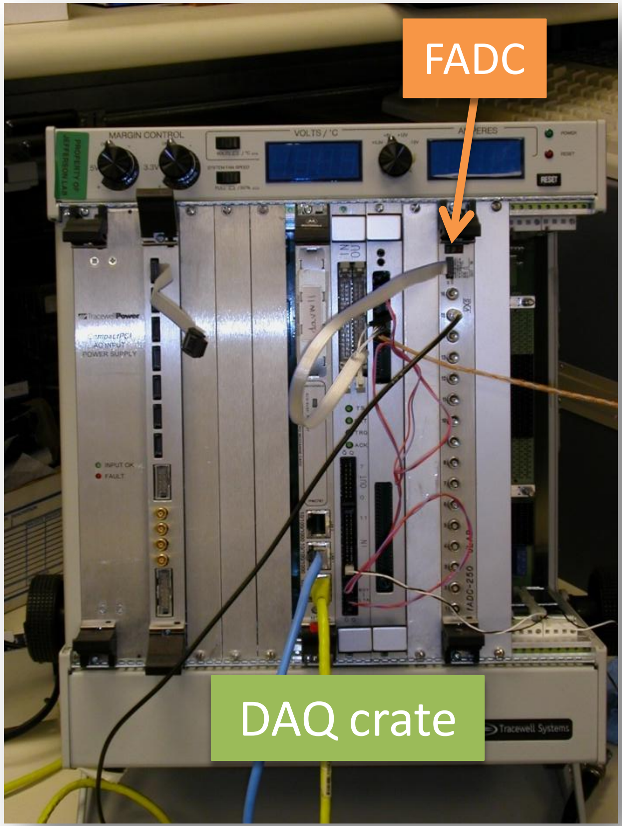
- Efficiency of experiments: **1/3**
- Lower temperature, 20ºC→5ºC, will reduce dark rate by a factor of **3**:
  - Will the radiation damage change this factor?
  - How about the damage and recovery rate with lower temperature?
- Assuming both factors valid:
  - H_2 target: **8 – 10 years**
  - He target: **5 – 7 years**

Test of Temperature Dependence

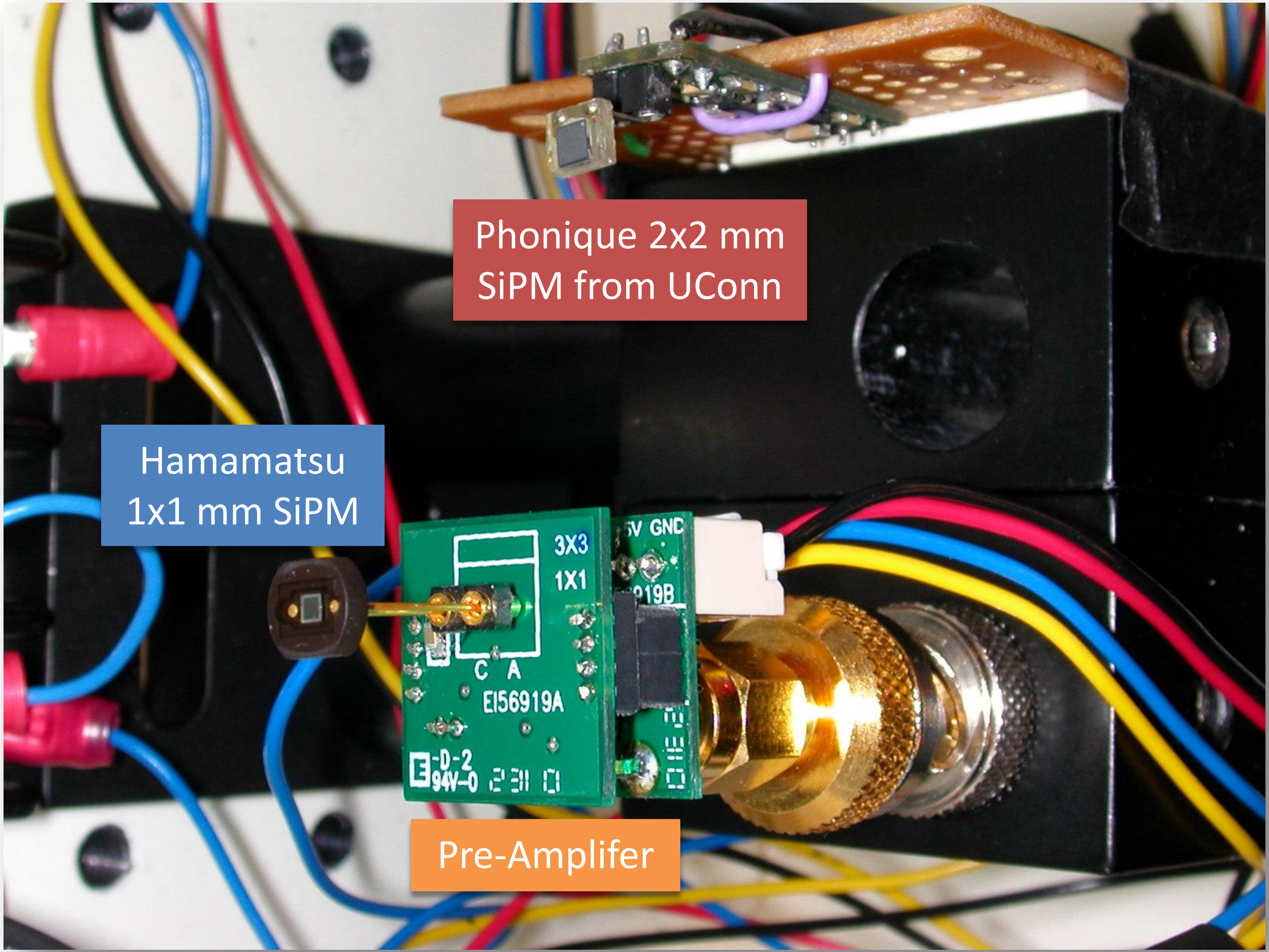
- Ordered 15 1x1 mm SiPMs from Hamamatsu: arrived last Thursday.
- Test plan:
  - Irradiation with AmBe source at two temperatures:
    - room temperature and 0°C.
  - Recovery at three temperatures:
    - 60°C, room temperature and 0°C.
  - 6 combinations and 2 samples for each combinition.
- Sascha Somov helped set up a DAQ in F117 using FADC.

The Test Setup in F117

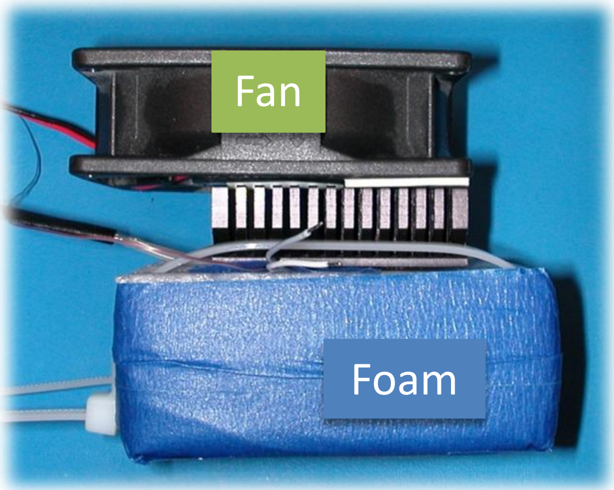




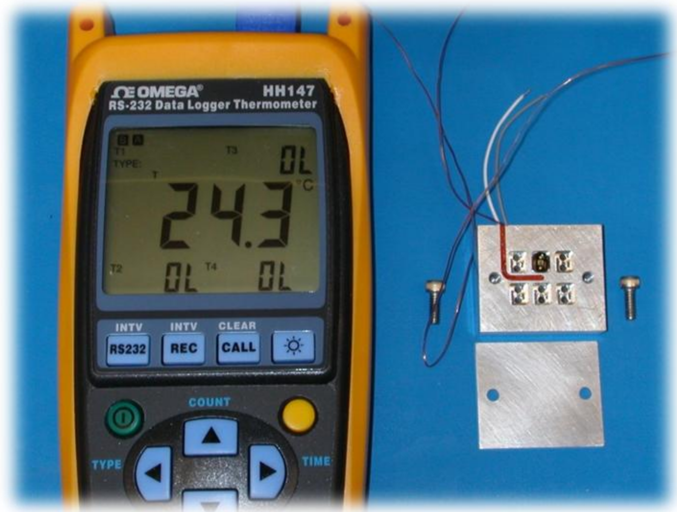
Inside the Black Box

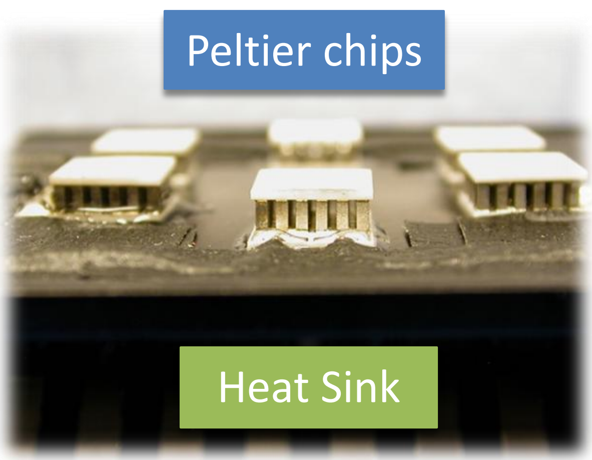


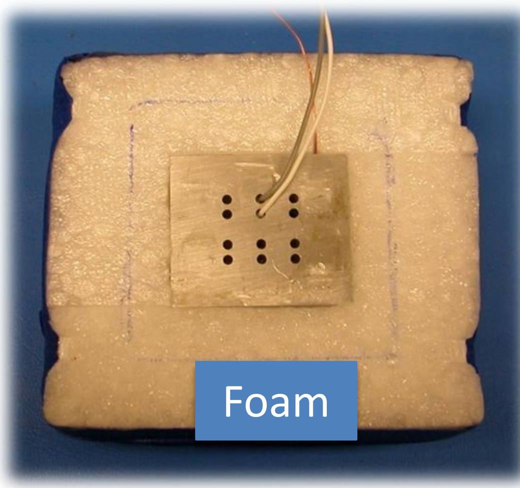
The Cooling Device

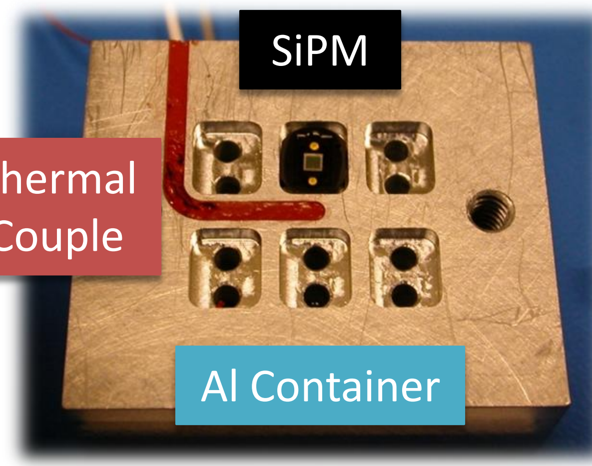


With six Peltier effect chips, the device can cool six SiPMs to -10°C at 25°C room temperature.



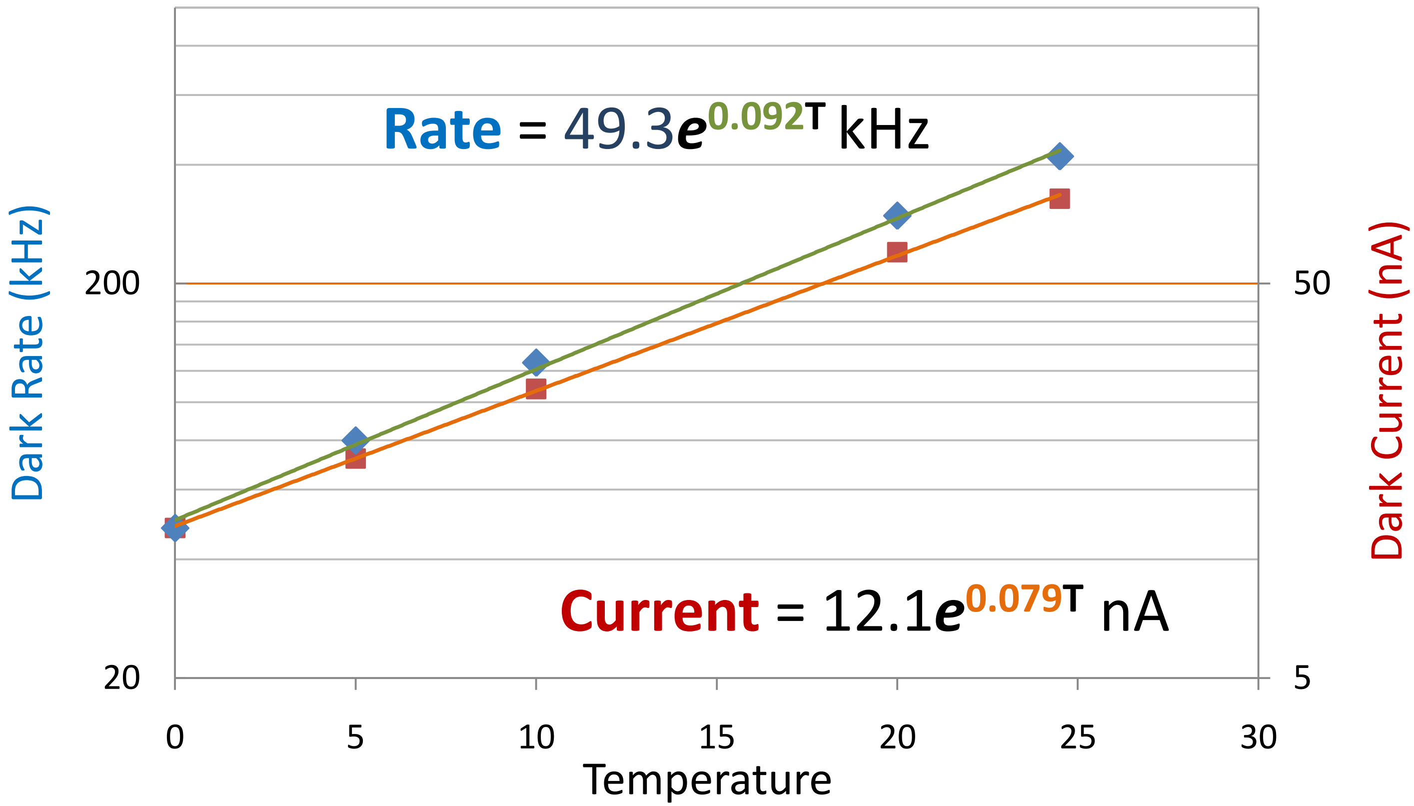






Temperature Dependence

- Hamamatsu: Dark rate = A $e^{0.082\,T}$ with fixed gain.
- Both measured dark rate and dark current are consistent.

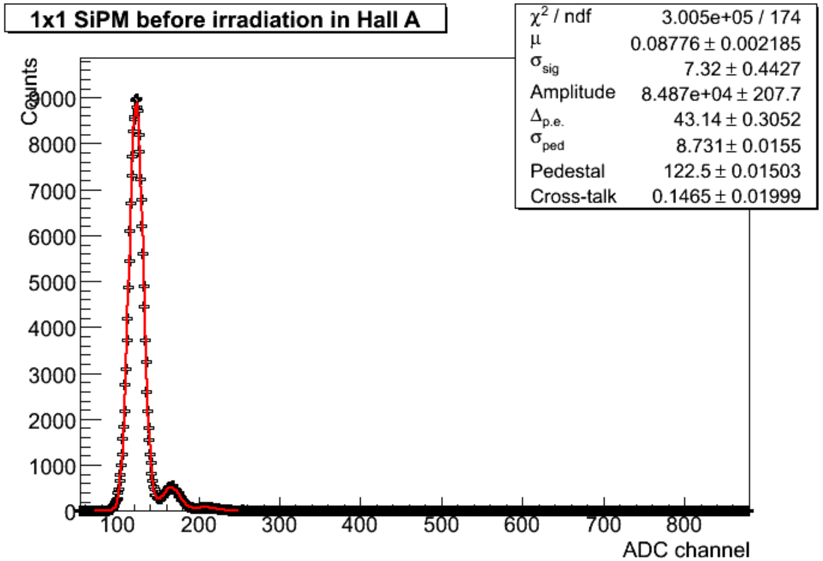


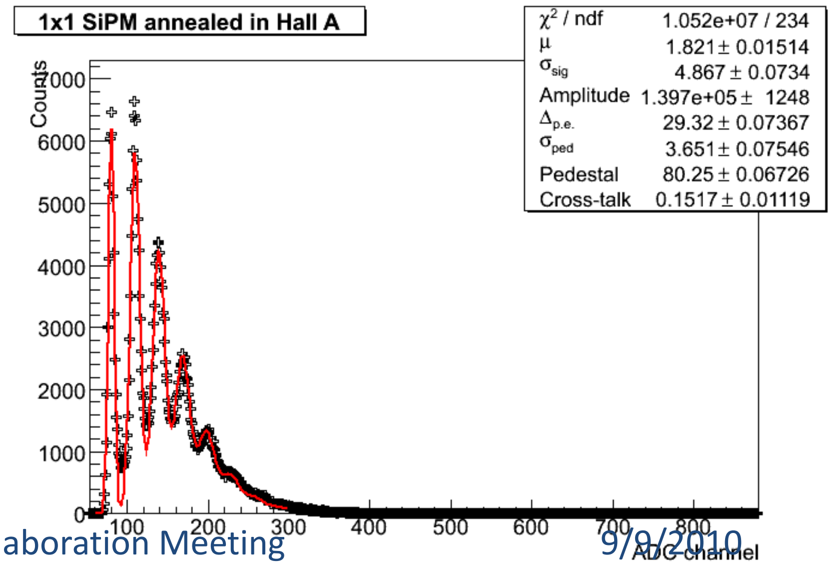
What's Next

- Basic properties of all 15 SiPMs have been measured at room temperature:
  - Dark current, dark rate, response to LED pulses and V-I curves.
  - All samples show consistent performance.
- Measured temperature dependence of one sample:
  - Meets the specification.
  - Will test several other samples.
- Begin irradiation test together with some previously irradiated samples.
- Sascha Somov is doing simulation with FLUKA to compare with GEANT simulation.

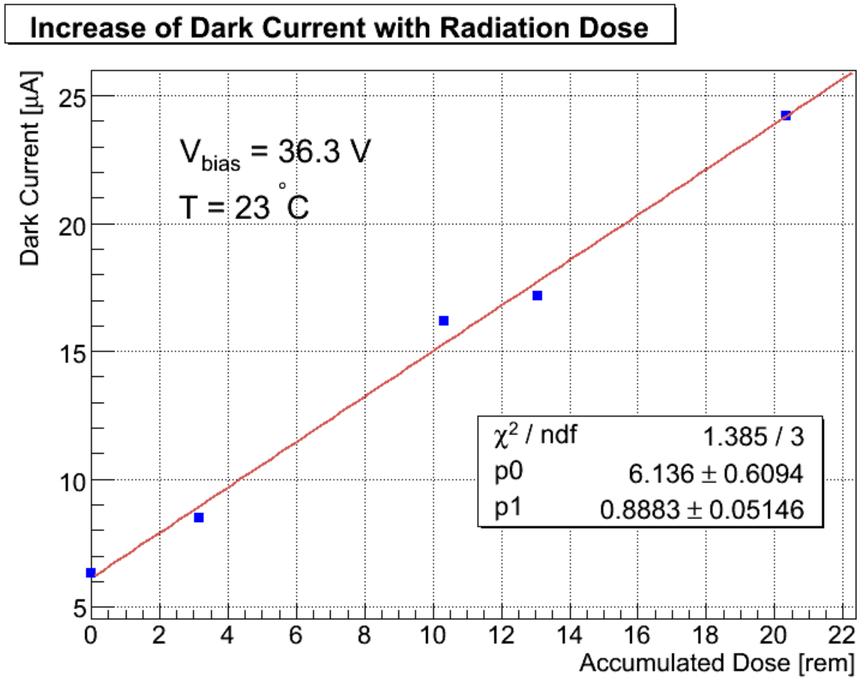
The 1x1 mm SiPM irradiated in Hall A

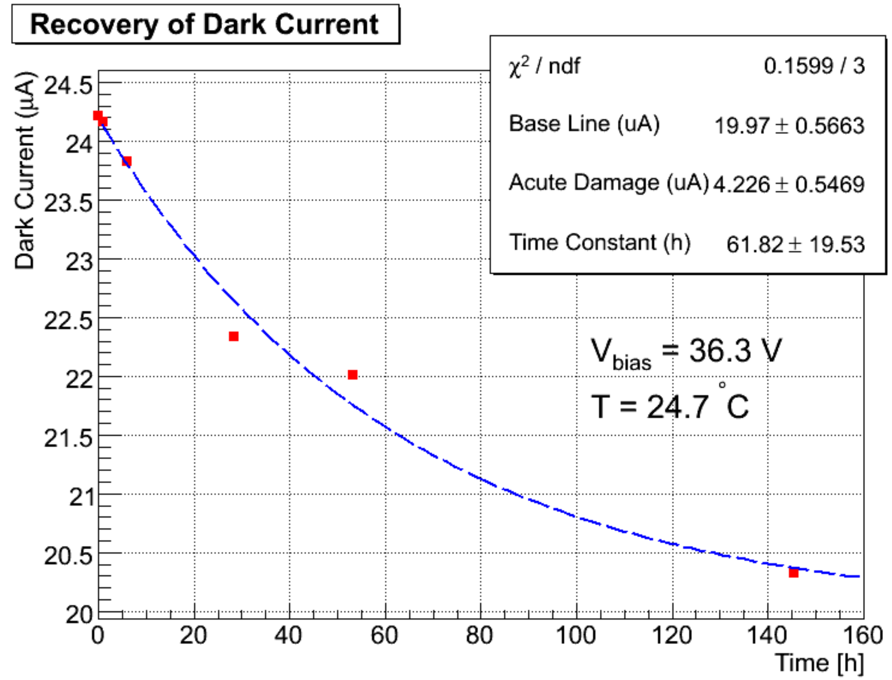
- The 1x1 mm SiPM irradiated in Hall A showed abnormally high dark rate: 2.6 times higher than other samples.
- Investigations are under way:
  - Odds for greater damage?
  - Beam scraping?
- Carl is checking the individual tiles of the irradiated 4x4 arrays in Hall A to see the uniformity of the damage.





Results of Photonique 2x2 mm SiPM





- Irradiated by AmBe Source to 20 rem.
- Similar damage rate as SensL SiPM.
- Recovery measurement still on-going.

Acknowledgement

- Many thanks to:
  - Carl Zorn
  - Fernando Barbosa
  - Pavel Degtiarenko
  - Sascha Somov

JLAB-TN-11-005
GlueX-doc-1660
Version 0.3
February 23, 2011

Calculation of Radiation Damage to Silicon Photomultipliers in GlueX Experiment

P. Degtiarenko, A. Fassò, G. Kharashvili, A. Somov

Abstract

Understanding the effects of neutron radiation is critical for operation of silicon photomultipliers, the photodetectors which are planned to be used in the barrel electromagnetic calorimeter and the Start Counter detector of the GlueX experiment. Neutron radiation damage and dose equivalent rates were computed using two independent simulation packages: FLUKA and GEANT3.

1 Introduction

Silicon photomultipliers (SiPM) are a relatively new type of photodetector currently being used in various experiments in nuclear and high energy physics. Most characteristics of SiPMs, such as a timing resolution, quantum efficiency and gain, are comparable with that of traditional PMTs. However, the ability to operate SiPMs in large magnetic fields makes these photodetectors attractive for many applications in calorimetry and time-of-flight measurements.

In the GlueX experiment at Jefferson Lab, SiPMs are planned to be used as photodetectors for the barrel electromagnetic calorimeter (BCAL) and the Start Counter (SC) detector. Both, the BCAL and the SC will be positioned inside a 2.2 T solenoid magnet. The BCAL is a 3.9 m long cylindrical detector with the inner and outer radii of 65 and 90 cm, respectively. It is made of 180 layers of lead sheets and scintillator fibers placed in lead grooves between the layers. The BCAL is divided into 48 sectors (modules), each of which is organized into 40 readout blocks per end (side). Light from scintillator fibers of each readout block will be detected by a single SiPM sensor array. The effective area of the SiPM array is $1.2 \times 1.2\ cm^2$.

The SC is a cylinder-shaped detector consisting of 40 scintillator paddles positioned around the GlueX liquid hydrogen target. Light produced in the scintillator is detected from the upstream side of each paddle by a few SiPMs array sensors.

Recent radiation tests of SiPMs performed at Jefferson Lab [1] showed a relatively large sensitivity of these photodetectors to neutron radiation. Specifically, an accumulated dose of 32 rem from an AmBe neutron source increased the dark current of Hamamatsu SiPMs by a factor of 4.4. Similar behavior of the dark current was observed when the SiPMs were exposed to neutron radiation in experimental Hall A [1].

In order to estimate the degradation of the BCAL and SC SiPM's performance in the Hall-D, we performed a detailed simulation of the neutron background using a GEANT program provided by the JLab radiation control (RadCon) group and a FLUKA program. The SiPM dark current increase can be estimated by comparing neutron doses predicted by the simulations with that acquired during the radiation tests. The RadCon GEANT is based on the standard GEANT 3 but includes a better description of the photo/electro-nuclear processes.

During the SiPM radiation tests, neutron doses were measured by a neutron survey meter. The neutron survey meter measures the so-called equivalent dose in units of rem, which accounts for different biological effects to tissue of different types of ionization. The neutron flux and energy can be translated to the equivalent dose using a biological damage coefficients curve presented in the upper plot of Fig. 1. Damage effects to Silicon detector caused by different particle types (which lead to the displacement of atoms in the crystal lattice and are associated with the kinetic energy releases to matter) can be characterized by a damage function presented in the bottom plot of Fig. 1. The curves on this plot correspond to different particle types and are normalized to an equivalent damage of 1 MeV neutrons. The shape of the biological damage coefficients curve of neutrons is somewhat similar to that of the damage function in Silicon. In order to compare damage effects to Silicon caused by different particle types with different energies, it is convenient to convert the particle fluence to the equivalent fluence of 1-MeV neutrons using the damage function presented in Fig. 1.

This note is organized as follows: in Section 2 we will describe the Monte-Carlo detector simulations and some physics models included into the GEANT and FLUKA programs. The simulation results will be presented and discussed in Sections 3 and 4.

2 Monte-Carlo Modeling

The main goal of the GlueX experiment is to search for mesons with exotic-quantum-numbers in interactions of a linearly polarized photon beam with a 30 cm long liquid hydrogen target. The high-intensity photon beam will be produced via the Bremsstrahlung process by a 12 GeV electron beam incident on a thin diamond radiator. In order to increase the fraction of linearly polarized photons, the photon beam is passed through a 3.4 mm diameter collimator. The flux of the collimated photons is about a $3.4 \cdot 10^9$ γ/s in the beam energy range 1.2 MeV $< E_\gamma <$ 12 GeV, corresponding to a total beam power of about 0.7 W on the target. The energy spectrum of the collimated beam photons is presented in Fig. 2. The coherent peak in the energy spectrum between 8.4 GeV $< E_\gamma <$ 9.0 GeV represents the photon beam energy range of interest used for the search of exotic mesons. The degree of linear polarization in this energy region is 40%. The low-energy part of the energy spectrum can be relatively well parametrized by a 1/E function. The energy spectrum from Fig. 2 was used as an input for both GEANT and FLUKA simulations.

The official GlueX detector simulation is based on GEANT 3.21. The GEANT geometry contains a detailed description of the GlueX detector and is presented in the top plot of Fig. 3. In order to verify neutron fluences predicted by GEANT we compared particle distributions inside the detector using the FLUKA simulation. In the FLUKA simulation we used a simplified GlueX geometry, that is expected to represent reasonably well the detector material and major sources of particle scattering. The FLUKA geometry is shown in the bottom plot of Fig. 3. The geometries of the gaseous detectors (the Central Drift Chambers (CDC) and the Forward Drift Chambers (FDC)) have been greatly simplified relative to their full description in GEANT. The main geometry simplifications are listed below:

- The Central Drift Chamber was modeled as a tube filled with an admixture of 85% Ar and 15% CO_2 gases. 24 layers of CDC straw tubes containing wires were grouped into 3 rings. The thickness and equivalent material of each ring corresponded to that of 8 straw layers. Two rings were placed at the inner and outer radii of the CDC layers corresponding to 9 cm and 55.6 cm, respectively, and the third ring was positioned in between them. The CDC geometry contains two endplates situated at the upstream and downstream ends of the gas volume.

- The Forward Drift Chamber consists of 4 packages positioned at different z coordinates inside the solenoid magnet. Each package contains 6 cathode-wire-cathode sandwich chambers filled with an $ArCO_2$ gas. The geometry of each package in FLUKA was modeled as four tube-shaped volumes. The volumes were filled with an average material and represented the following parts of the chambers: (1) the FDC ground plates made of Aluminized Mylar; (2) the gas volumes; (3) the outer part of cathode plates with the inner radius of 1.3 cm made of Kapton and covered with Copper; (4) the inner part of cathode plates made of Kapton and positioned inside the photon beamline with the outer radius of 1.3 cm. We also implemented into the geometry volumes corresponding to frames of the FDC chambers and FDC cables going from from each package to the upstream end of the CDC chamber. The frames were modeled as cylinders with the inner and outer radii of 51 cm and 53 cm, respectively made of a composite material consisting of 70% Borosilicate Glass and 30% Epoxy Resin. The FDC cables were simulated as a cylinder made of PVC and Copper with inner and outer radii of 62.5 cm and 62.61 cm, respectively.

- The geometry of a Cerenkov gaseous detector was simplified to a tube filed with C_4F_{10} gas and positioned after the solenoid magnet. Detector mirrors were not included into the geometry. The Cerenkov detector will not be used at the early stage of the GlueX experiment and will be installed in the future upgrade of the experiment.

- The field map of the solenoid magnet implemented in the GEANT simulation was obtained using a TOSCA magnetic field simulation package [2]. The B_z component of the magnetic field for different radial distances from the beamline as a function of the Z-coordinate is presented in Fig. 4. As can be seen, the value of B_z is almost independent of the radial distance from the beamline, r. Therefore, in the FLUKA simulation we neglected the field dependence on the radial distance and implemented the B_z shape from Fig. 4 corresponding to $r = 0$. The magnetic field shape was parametrized using a polynomial function.

2.1 GEANT

The GEANT simulation provided by the Radiation Control group represents the standard GEANT3 with a better description of photo/electro-nuclear interactions. The modifications to the standard GEANT3 include replacement of the 'PFIS' (photofission) mechanism with the photonuclear absorption mechanism in accordance with total photonuclear cross sections and invoking a nuclear fragmentation event generator, DINREG, to produce secondary hadrons in these interactions. The code DINREG was developed by Pavel Degtiarenko and Mikhail Kossov. The generator is exclusive, meaning that it generates fragmentation events fully conserving 4-momentum, baryon number and charge in the reaction. Nuclear fragmentation at high energies is described in the model as a two-stage process. First is the energy deposition in the nucleus by the projectile particle, specific to the type of the particle (hadrons, leptons, photons, etc.), with the probability proportional to the total inelastic cross section. The second stage is the process of dissipation of the deposited energy into production of secondary hadrons and nuclear fragments. The second stage is universal and common to high energy nuclear reactions by different projectiles, as it was observed in many hadron-nuclear experiments at medium and high energies (see refs. [5]- [6]). DINREG/GEANT3 implementation at JLab was based on application of the model principles to the case of incident gammas, producing the model for the first stage energy deposition by energetic photons in nuclei, and then utilizing the nuclear fragmentation model to generate secondary hadrons and fragments explicitly.

Another modification is the new process of electro-nuclear interaction which assumes that the low-Q2 interactions of electrons with nuclei can be described in terms of the Equivalent Photon Approximation (EPA), using real photon cross sections for the equivalent photons and then modeling the interaction analogous to the gamma-nucleus process. The electron interactions are modeled as the interaction of the flux of equivalent photons along each electron step in the cascade. No high-Q2 processes are thus modeled, assuming all electron interaction is energy loss in the forward direction. This approximation is good enough for practical purposes of bulk background calculations, but of course fails to describe details of large angle, deep inelastic electron scattering, as well as the quasielastic electron scattering off nuclei. The results should in general be accurate within factors of 2-3, but may be worse for very forward hadron production. The electron scattering at large angles could be underestimated.

The code is used extensively at JLab for background and shielding calculations, as the neutron photoproduction contributes significantly to radiation background problems at CEBAF. No detailed reference with the description of the GEANT/DINREG code system exists. DINREG was described in an ITEP preprint [3] and not published later; there are several papers referring to the results of its use, mostly in detector acceptance calculations [4]. Ref. [5] describes the use of the GEANT/DINREG model in shielding calculations at CEBAF.

Further development of the underlying Physics model of the Chiral Invariant Phase Space (CHIPS), and its implementation in the new Geant4 simulation toolkit was sponsored by JLab and performed by M.Kossov. The new, completely rewritten in c++ version of the CHIPS Monte Carlo is included in Geant4, with the proper model description and benchmark tests [6].

2.2 FLUKA

FLUKA [7, 8] is a multi-purpose Monte Carlo code for particle transport and interactions, which is capable of simulating all components of hadronic and electromagnetic cascades from very high energies down to thermal neutrons. FLUKA is used in a large number of very different applications: accelerator shielding and activation, dosimetry and radiation protection, calorimetry, cosmic ray research, hadron therapy, etc. A further common application is to predict radiation damage. Its predictive power has been confirmed by a large number of benchmarking studies, comparing FLUKA results against experimental data. The code is provided with a number of statistical tools (biasing options) to reduce the variance of the results.

To predict radiation damage, the probability for a displacement damage to occur due to non-ionizing energy loss (NIEL) is calculated by scoring the 1-MeV neutron equivalent fluence of all particles in the regions of interest, weighted with published damage cross sections [9]. The probability of single event upsets (SEU) is calculated using the fluence of particles with energies >20 MeV and the available SEU cross section data [10].

2.2.1 The FLUKA physics models

Several different models are used by FLUKA to simulate particle transport and interactions. Charged particle transport is based on Bethe-Bloch ionization and Moliere multiple scattering, including some higher order corrections. It is possible to transport charged particles in magnetic fields described by the user. Electron, positron and photon electromagnetic interactions include bremsstrahlung, positron annihilation at rest and in flight, Rayleigh and Compton scattering on bound electrons, fluorescence, Auger and pair production; in all these interactions the energy and angle of the secondaries are fully correlated.

The physical interaction models of interest for the present note concern the hadronic and the photonuclear interactions. The PEANUT event generator is based on different models describing energy-dependent hadron inelastic interactions: Glauber-Gribov cascade with formation zone, Generalized IntraNuclear Cascade (GINC), preequilibrium stage with current exciton configuration and excitation energy, evaporation (or Fermi break-up or fission), and gamma de-excitation.

The photonuclear reactions at different photon energies are Giant Resonance, Quasideuteron, Delta Resonance and Vector Meson Dominance with shadowing. The total interaction cross section is tabulated or parametrized according to experimental data. The nuclear de-excitation and emission of secondaries are handled by the hadronic event generators listed above.

3 Results

Particle fluences in the SiPM region at the downstream end of the BCAL obtained using the FLUKA and GEANT simulations are presented in Fig. 5. The particle fluences were averaged over a ring with the inner and outer radii of 66 cm and 76 cm from the beamline, respectively. The particle spectra were found to be in a relatively good agreement between the GEANT and FLUKA simulations. The difference in neutron fluences between GEANT and FLUKA is smaller than a factor of two for neutrons with a kinetic energy larger than 0.1 MeV, i.e., in the energy range where damage to Silicon dominates.

Fluences of all particles inside the GlueX detector obtained using the FLUKA simulation were scaled to a 1-MeV neutron equivalent fluence in Silicon using the damage function coefficients from Fig. 1. The 1-MeV neutron equivalent fluences of all particles and neutrons only are presented in Fig. 6. The 1-MeV neutron equivalent fluences computed in the Start Counter and BCAL SiPM regions for liquid Hydrogen and Helium GlueX targets are listed in Table 1. The SiPM regions are defined as follows:

1. **Start Counter.** Fluences were averaged over a ring with the inner and outer radii of 7 cm and 8 cm, respectively. The ring was positioned at the end of the Start Counter scintillator counters at Z = 40 cm.

2. **BCAL upstream SiPMs.** Fluences were averaged over a ring with the inner and outer radii of 66 cm and 76 cm, respectively. The ring was positioned at the end of the 15 cm long light guides in the upstream end of the BCAL at Z = -15 cm.

3. **BCAL downstream SiPMs.** The same ring size as in (2). The ring was situated after 15 cm long light guides at the downstream end of the BCAL at Z = 417 cm.

4. **75 cm downstream from BCAL.** The same ring radii as in (2)-(3). The ring was moved downstream the beam and was positioned at a distance of 75 cm from the downstream edge of the BCAL at Z = 492 cm.

As can be seen, the 1-MeV equivalent fluence in the BCAL SiPM region is dominated by the neutron background. Other types of background particles, which originate mostly inside the GlueX target, are shielded by the BCAL material.

The FLUKA simulation predicts the neutron background at the downstream end of the BCAL for the Hydrogen target to be 18.0 $n_{eq} \cdot s^{-1} \cdot cm^{-2}$ after the BCAL light guides and 16.7 $n_{eq} \cdot s^{-1} \cdot cm^{-2}$ 75 cm downstream from the BCAL edge. These numbers can be compared with the neutron fluence of 30.5 $n_{eq} \cdot s^{-1} cm^{-2}$ estimated with the GEANT simulation 75 cm downstream from the BCAL edge. The 1-MeV equivalent fluence for the upstream BCAL SiPMs is found to be about one order of magnitude smaller.

1-MeV neutron equivalent particle fluence distributions in the experimental Hall-D estimated with the FLUKA simulation are presented in Fig. 7. The corresponding dose equivalent rate is shown in Fig. 8.

FLUKA, Liquid Hydrogen target

Position of control volume	n	p	π	e^-	e^+	Total
Start Counter	20.9	1.4	18.4	0.1	0.1	40.9 ± 3.1
BCAL upstream SiPM	2.0	0.1	0.3	0.0	0.0	2.4 ± 0.2
BCAL downstream SiPM	18.2	1.7	1.8	1.1	0.3	23.2 ± 0.6
75 cm downstream from BCAL	16.7	2.2	2.3	18.2	5.6	45.1 ± 1.0

GEANT, Liquid Hydrogen target

75 cm downstream from BCAL	30.5					

FLUKA, Liquid Helium target

Start Counter	112.1	34.8	14.7	0.2	0.1	162.9 ± 5.9
BCAL upstream SiPM	8.0	0.2	0.3	0.04	0.03	8.6 ± 2.2
BCAL downstream SiPM	23.0	2.1	2.2	1.0	0.3	28.7 ± 0.3
75 cm downstream from BCAL	21.1	2.7	2.5	20.1	6.8	53.7 ± 0.9

Table 1: 1-MeV neutron equivalent fluence in units of $n_{eq} \cdot s^{-1} \cdot cm^{-2}$ estimated with FLUKA and GEANT simulations. The fluences were computed in the Start Counter and BCAL SiPM regions. See definitions of the regions in the text.

4 Discussion

We have estimated background in the BCAL SiPM region using two independent simulation programs: the RadCon GEANT3 and the FLUKA. The background was computed in units of a 1-MeV neutron equivalent fluence in Silicon. This unit can be used to characterized the damage to the Silicon detectors caused by different particle types. The background in the SiPM region was found to be dominated by neutrons; the most background particles originating from the target are shielded by the BCAL material. The exceptions are SiPMs located closest to the beamline. The radiation damage of these SiPMs produced by other particle types is comparable to that from neutrons. Neutron fluences predicted by GEANT and FLUKA simulations were compared 75 cm downstream from the BCAL edge. The fluences for a Hydrogen GlueX target were found to be 30.5 $n_{eq} \cdot s^{-1} \cdot cm^{-2}$ and 16.7 $n_{eq} \cdot s^{-1} \cdot cm^{-2}$, respectively. The GEANT and FLUKA results are considered to be in satisfactory agreement. The discrepancy is due to:

1. Different physics models of photo-nucleus interactions used in GEANT and FLUKA simulations.

2. Simplified GlueX detector geometry used in the FLUKA simulation.

According to the irradiation tests of BCAL SiPMs performed at JLab in the experimental Hall A and using an AmBe neutron source, the dark current of the photodetectors is expected to be increased by about a factor of 5 for the accumulated neutron 1-MeV equivalent fluence between $0.8 - 1.9 \cdot 10^9$ $n_{eq} \cdot cm^{-2}$ [1]. That fluence corresponds to the continuous operation of the BCAL SiPMs for about 1-2 years assuming a background of 30.5 $n_{eq} \cdot s^{-1} cm^{-2}$.

The 1-MeV neutron equivalent fluence in the Start Counter SiPM region was estimated to be about a factor of two larger than that in the downstream BCAL SiPM region for the Hydrogen target. The SiPM dark current increase is expected to be not very critical for the timing measurements performed with the Start Counter [11].

References

[1] Neutron radiation tests performed by Yi Qiang `hhttp://www.jlab.org/Hall-D/software/wiki/index.php/SiPM_Radiation_Hardness_Test`.

[2] D. Lawrence and S. Taylor, "Track Finding and Fitting in GlueX: Development Report", GlueX-doc-1004, (2008).

[3] P. V. Degtyarenko et al., "Inelastic Electron-Nucleus Interactions at 5 GeV detected by ARGUS", Z.Phys.A, **335**, 231-238 (1990).

[4] P. V. Degtyarenko and M. V. Kossov, "Monte Carlo program for nuclear fragmentation", Preprint ITEP-11, 1-18 (1992). P. V. Degtyarenko et al., "Multiple hadron production by

14.5 GeV electron and positron scattering from nuclear targets", Phys.Rev.C, **50**, R541-R545 (1994).

[5] P. V. Degtyarenko, "Applications of the Photonuclear Fragmentation Model to Radiation Protection Problems", Proceedings of SATIF2, 12-13 October 1995 CERN, Geneva, Switzerland.

[6] P. V. Degtyarenko, M. V. Kossov, H-P. Wellisch, "Chiral Invariant Phase Space Event Generator I. Nucleon-antinucleon annihilation at rest", Eur. Phys. J. A **8**, p.217-222 (2000). P. V. Degtyarenko, M. V. Kossov, H-P. Wellisch, "Chiral Invariant Phase Space Event Generator II. Nuclear pion capture at rest and photonuclear reactions below the Δ(3,3) resonance", Eur. Phys. J. A **9**, p.411-420 (2000). P. V. Degtyarenko, M. V. Kossov, H-P. Wellisch, "Chiral Invariant Phase Space Event Generator III. Modeling of real and virtual photon interactions with nuclei below pion production threshold", Eur. Phys. J. A **9**, p.421-424 (2000).

[7] A. Fasso‘, A. Ferrari, J. Ranft, and P.R. Sala, "FLUKA: a multi-particle transport code" CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773.

[8] G. Battistoni, S. Muraro, P.R. Sala, F. Cerutti, A. Ferrari, S. Roesler, A. Fasso‘, J. Ranft, "The FLUKA code: Description and benchmarking" Proceedings of the Hadronic Shower Simulation Workshop 2006, Fermilab 6-8 September 2006, M. Albrow, R. Raja eds., AIP Conference Proceeding 896, 31-49, (2007).

[9] M. Huhtinen, and P.A. Aarnio, "Pion induced displacement damage in silicon devices". Nuclear Instruments and Methods A335, 580-582 (1993).

[10] G.P.Summers, et al., "Damage correlations in semiconductors exposed to gamma, electron and proton radiations". IEEE Trans. Nucl. Sci. 40, 1372-1379 (1993).

[11] R.T. Jones, Performance of the Hall D Tagger Microscope as a Function of Rate, December 30, (2010), `hhttp://zeus.phys.uconn.edu/halld/tagger/fp-microscope/rates-10-2009/rates.pdf`.

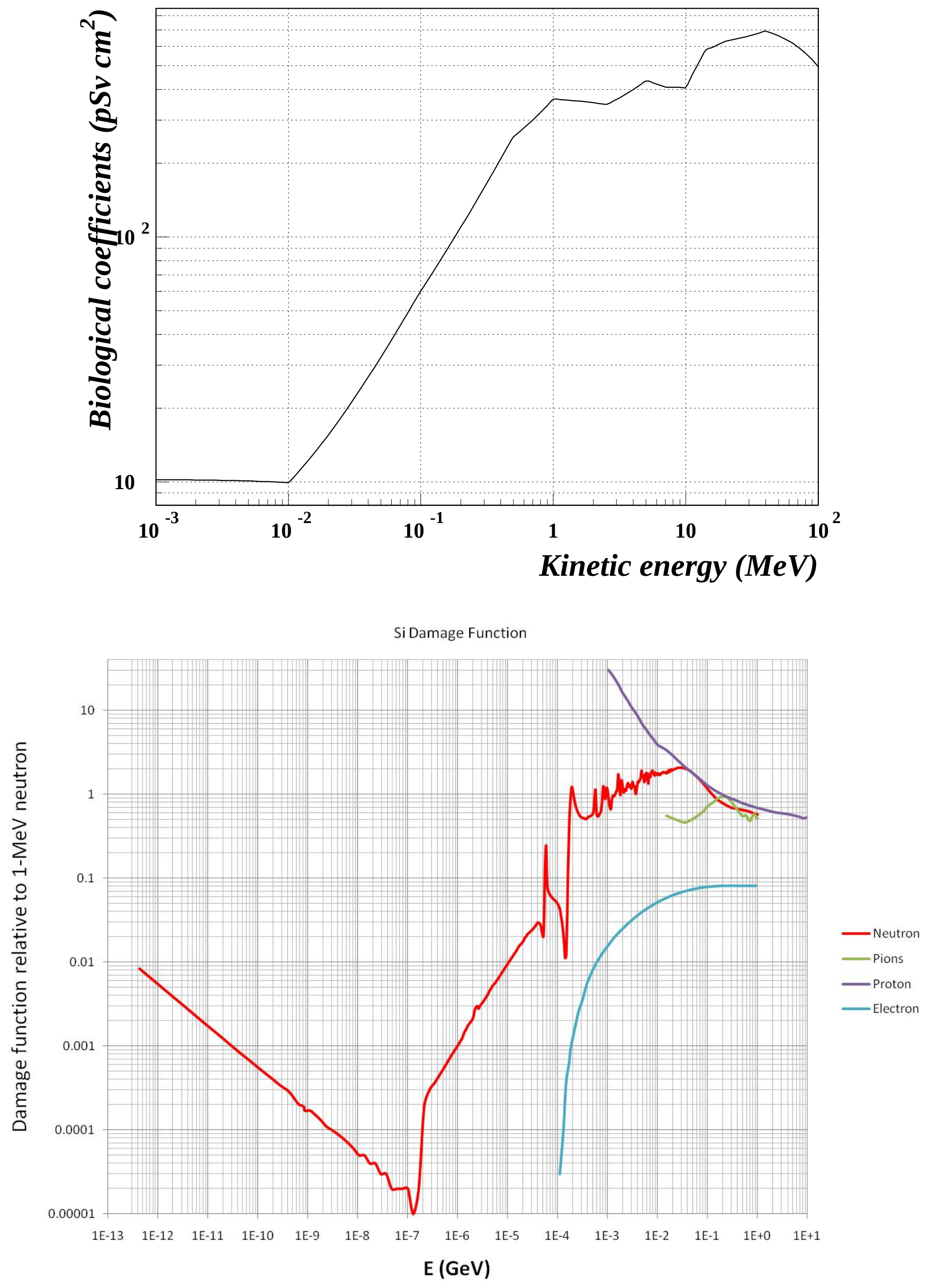


Figure 1: Biological damage conversion coefficients for neutrons (top). Effective damage to Silicon detector relative to 1-MeV neutron caused by different particle types (bottom).

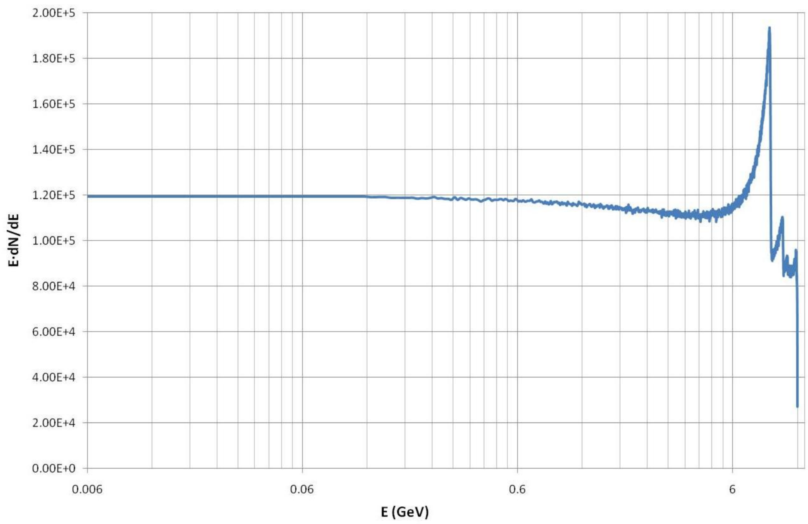


Figure 2: Energy spectrum of the GlueX photon beam after the collimator. This spectrum was used as an input for GEANT and FLUKA simulations.

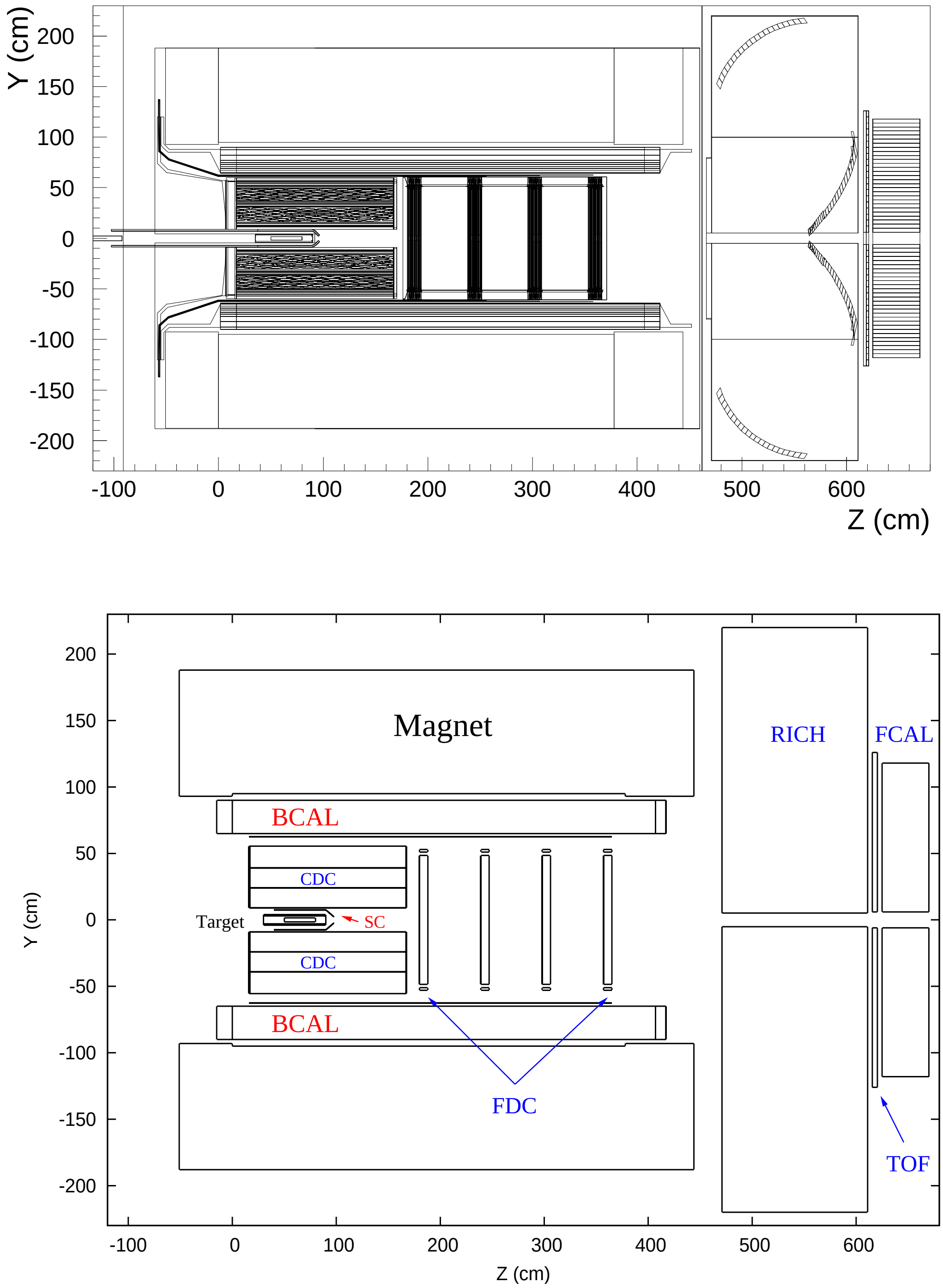


Figure 3: Plane view of the GlueX detector geometry implemented into GEANT (top) and FLUKA (bottom) simulations. GlueX sub-detectors are: Target, Start Counter (SC), Barrel Electromagnetic Calorimeter (BCAL), Central Drift Chamber (CDC), Forward Drift Chamber (FDC), Rich Cerenkov counter (RICH), Time-of-Flight counter (TOF), and Forward Electromagnetic Calorimeter (FCAL).

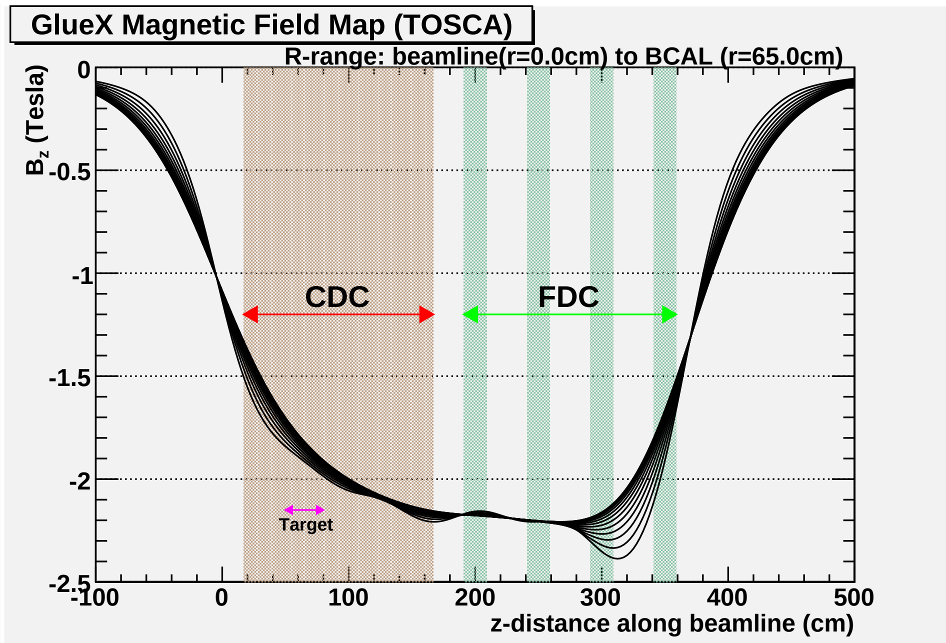


Figure 4: Magnetic field distribution inside the GlueX solenoid magnet obtained using TOSCA magnetic field simulation package.

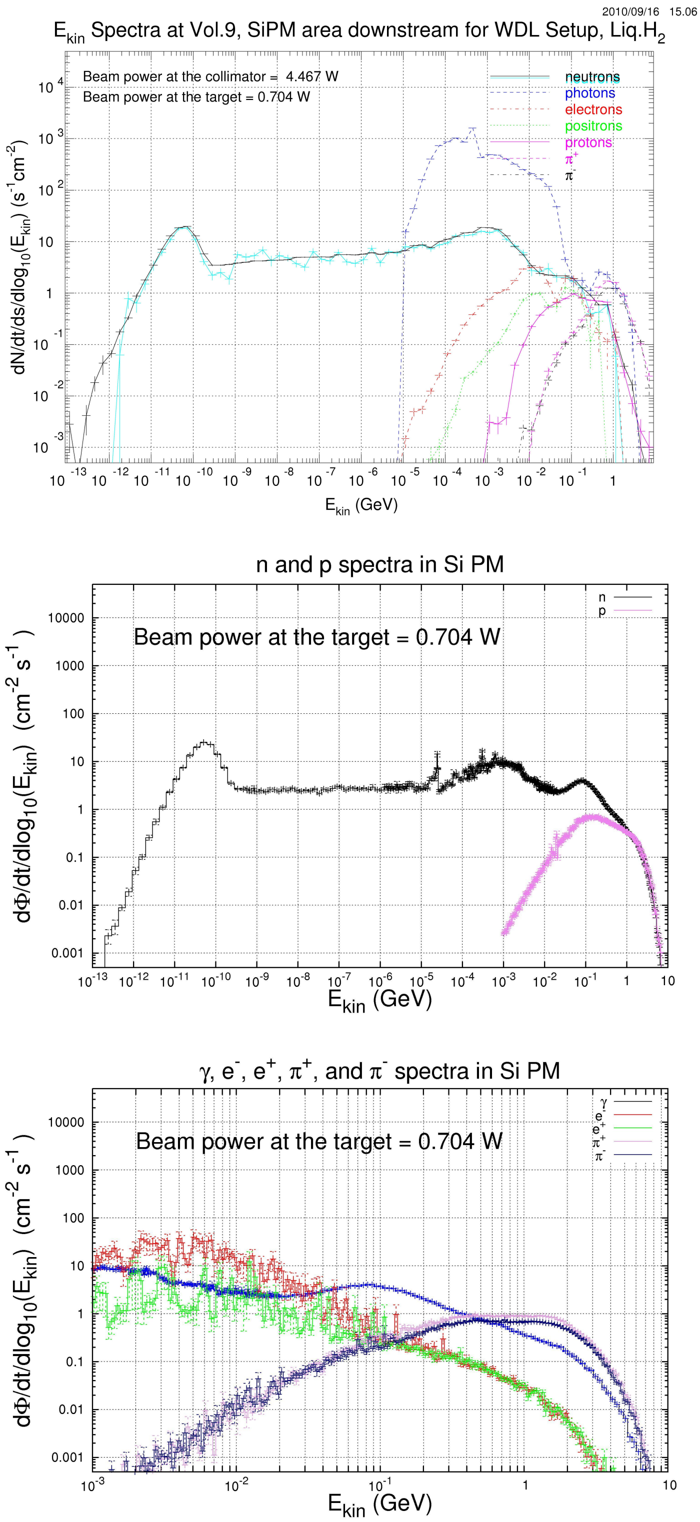


Figure 5: Particle spectra computed with the RadCon GEANT in the SiPM region (top). Corresponding particle fluences of neutrons and protons (middle) and other particle types (bottom) predicted by FLUKA simulation.

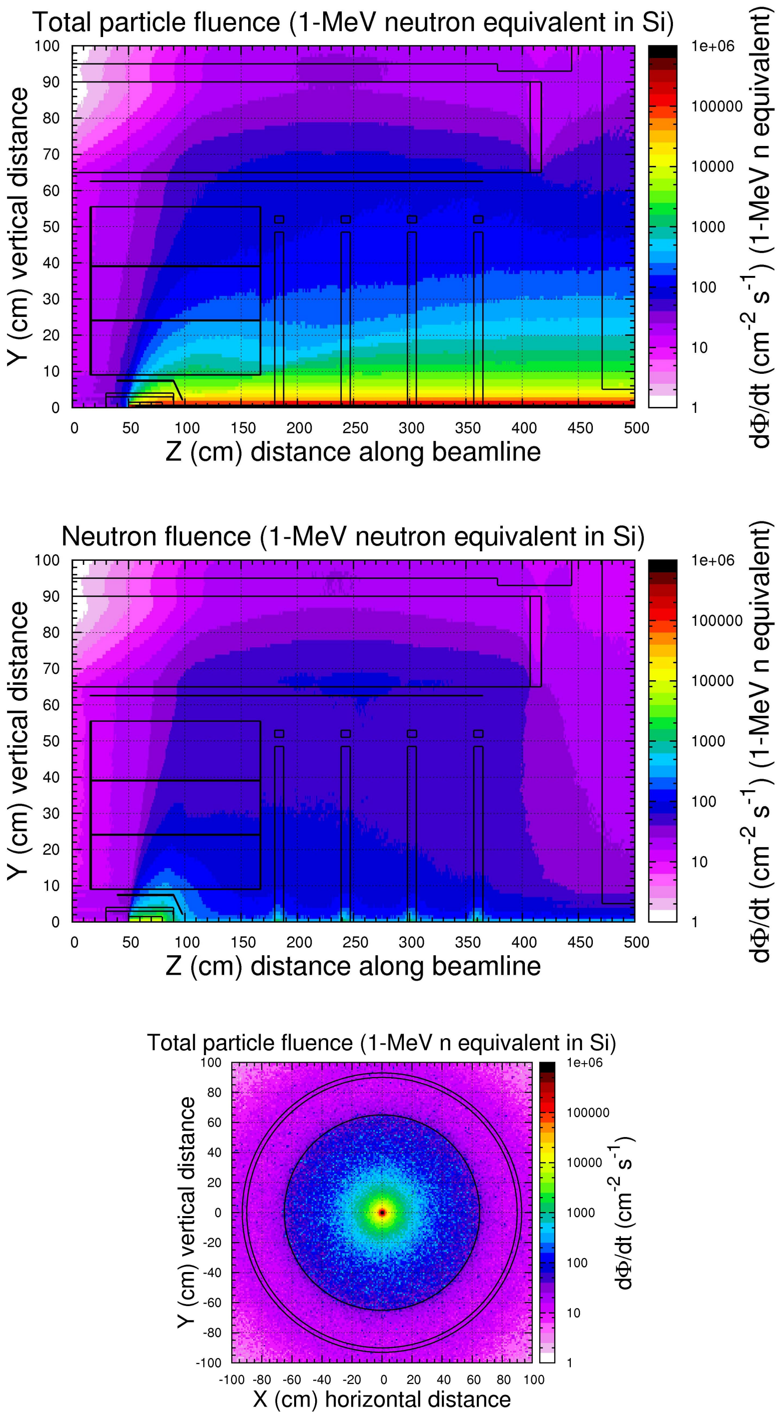
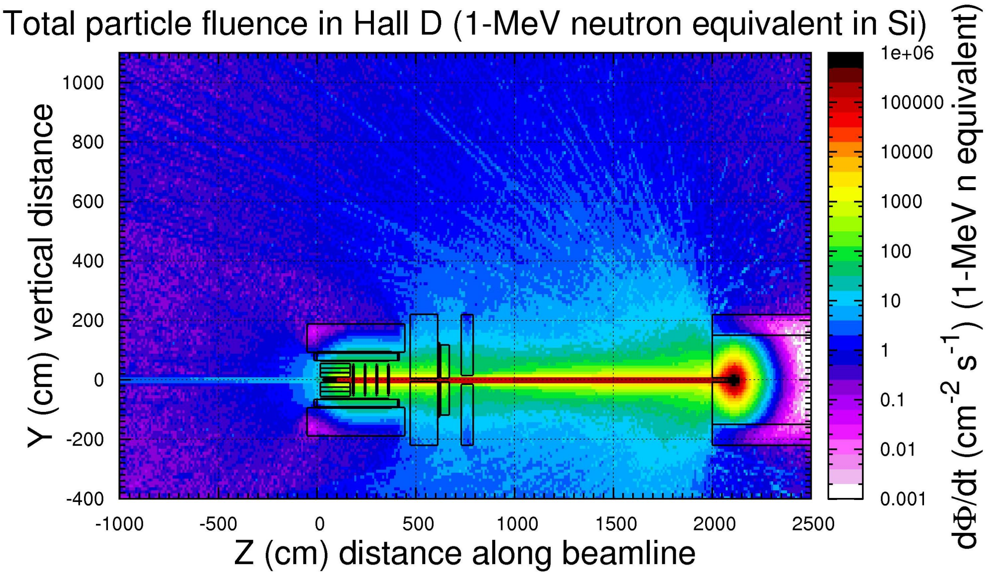


Figure 6: Total particle fluence (top) and neutron fluence (middle) inside the GlueX detector in 1-MeV neutron equivalent obtained with the FLUKA simulation. X-Y distribution of the particle fluence in the BCAL SiPM region is presented in the bottom plot. The BCAL is contained within the plotted ring between $r = 65$ cm and 90 cm.



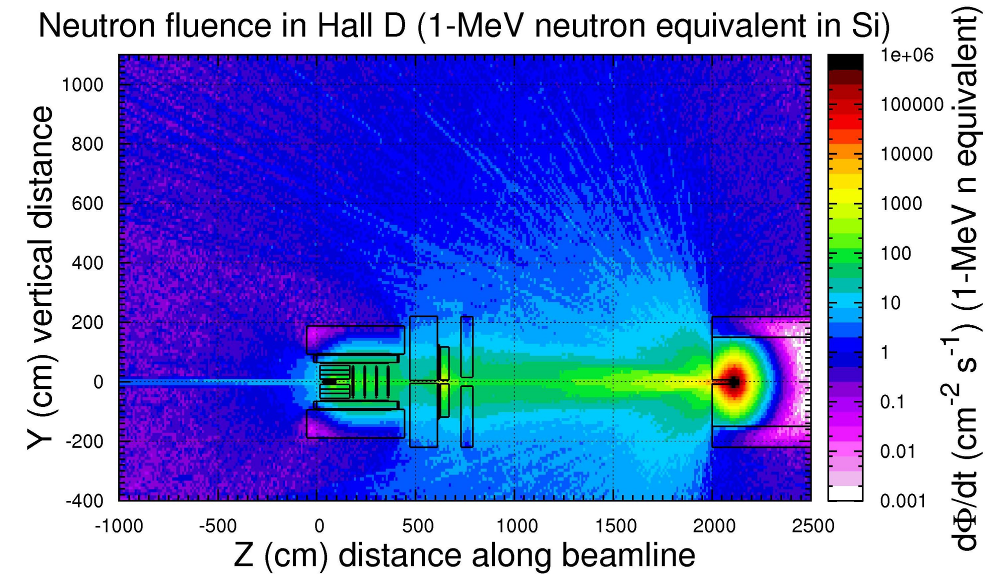


Figure 7: 1-MeV neutron equivalent in Silicon fluences of all background particles (top) and neutrons (bottom) in the experimental Hall-D estimated with FLUKA simulation. Most of the energy is deposited in the photon beam dump (box on the right side of each plot).

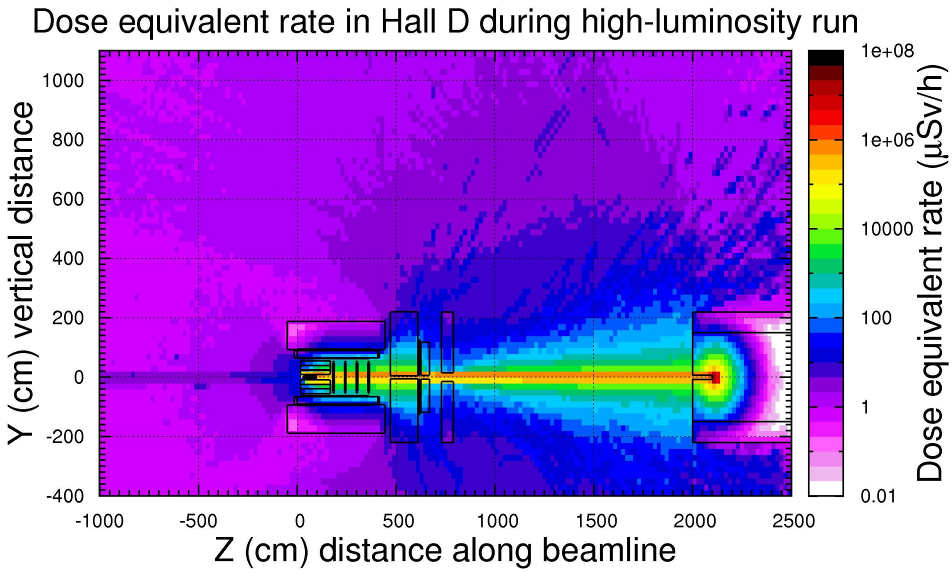


Figure 8: Dose equivalent rate in the experimental Hall-D estimated with FLUKA simulation.

HAMAMATSU CORPORATION

Corporate Offices
360 Foothill Road, Box 6910, Bridgewater, New Jersey 08807-0910
Phone: (908) 231-0960 • Fax: (908) 231-1218 • Email: usa@hamamatsu.com

April 4th, 2011

Thomas Bailey
Hamamatsu Corporation
360 Foothill Road
Bridgewater, NJ 08807

Dr. Carl Zorn
Staff Scientist
Jefferson Laboratory
12,000 Jefferson Avenue
Newport News, VA 23606

Dear Dr. Zorn:

We are writing to express our high level of enthusiasm for your project "Proposal to Test Improved Radiation Tolerant Silicon Photomultipliers." Hamamatsu is very interested in collaborating with Jefferson Laboratory on the increasing the radiation tolerance of the MPPC detector. Your experience with testing this device for the effects of irradiation will insure a high probability of success towards this goal.

The improved radiation hardness of the MPPC detector is considered a critical theme in the progressive development cycle of this product line. Hamamatsu already has some general plans to help increase the radiation hardness by improving the starting materials and material processing. These improvements would serve to reduce the dark count levels of MPPC detectors. Another approach will be to modify the device structure in order to reduce the damage (i.e., dark rate increase) created by radiation. We believe that we will have our first sample of radiation hardened devices ready for Jefferson Laboratory testing and evaluation by late this summer. Hamamatsu is willing to provide samples and custom array designs to Jefferson Laboratory at a reasonable NRE fee estimated to be in the range of $30 to $35k.

Based on the years of successful collaboration between Hamamatsu and Jefferson Laboratory, we are confident of a successful and mutually beneficial collaboration.

Regards,

Thomas P Bailey

Thomas Bailey
South East Regional Sales Engineer
(P) 516-431-2870 | (F) 516-706-0412
http://sales.hamamatsu.com